ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

A NOVEL APPLICATION OF SMART HUMAN CENTRIC LIGHTING WITHIN THE SCOPE OF ENERGY EFFICIENCY AND COMFORT ASSESSMENT CRITERIA

Ph.D. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ENERJİ VERİMLİLİĞİ VE KONFOR DEĞERLENDİRME KRİTERLERİ KAPSAMINDA AKILLI İNSAN ODAKLI AYDINLATMA UYGULAMASI

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Date of Submission : 24 May 2024
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To my family and spouse,

This thesis is dedicated to Ömer Faruk VURUR, and my beloved family, whose love and support exceed all bounds.

Sevda ALIPARAST

FOREWORD

This study was conducted at the Energy Institute of Istanbul Technical University. First and foremost, I extend my heartfelt gratitude to my advisor, Prof. Dr. Sermin ONAYGİL, for generously sharing her knowledge and experience with me, providing invaluable guidance, and motivating me throughout this study.

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This thesis is dedicated to Ömer Faruk VURUR and my beloved family, whose boundless love and support have been my anchor.

July 2024 Sevda ALIPARAST

TABLE OF CONTENTS

Page

ABBREVIATIONS

AII	: Amacrine Cells
ANOVA	: Analysis of variance
CBCs	: Cone Bipolar Cells
CCT	: Correlated Color Temperature
CI	: Confidence Interval
CIE	: International Commission on Illumination
CRI	: Color Rendering Index
CS	: Circadian Stimulus
EML	: Equivalent Melanopic Lux
HCL	: Human Centric Lighting
IEA	: International Energy Agency
ipRGCs	: intrinsically photosensitive Retinal Ganglion Cells
IWBI	: International WELL Building Institute
LED	: Light Emitting Diode
LGN	: Lateral Geniculate Nucleus
L1	: Direct Suspended Linear Luminaire
L2	: Direct and Indirect Suspended Linear Luminaire
LRC	: Lighting Research Center
MANOVA	: Multivariate Analysis Of Variance
M-EDI	: Melanopic Equivalent Daylight Illuminance
MR	: Melanopic Ratio
OLH	: Optimum Luminaire Height
Q1	: Questionnaire 1
Q2	: Questionnaire 2
RBC	: Rod Bipolar Cells
SPD	: Spectral Power Density
UL	: Underwriters Laboratories

SYMBOLS

CLA	: Circadian light
E	: Error
EH	: Horizontal illuminance
Eλ	: Spectral irradiance distribution
EV	: Vertical illuminance
H	: Height
K	: Kelvin
LC	: L cone opsin
Lumen	: Luminous flux
Lux	: Illuminance
M	: Melanopsin
M(λ)	: Melanopsin sensitivity function
MC	: M cone opsin
mpλ	: Macular pigment transmittance
S(λ)	: SPD of the source
SC	: S cone opsin
Sλ	: S-cone fundamental
T	: Temperature
t	: Time
Vλ	: Photopic spectral sensitivity function
V′λ	: Scotopic spectral sensitivity function
W	: Watt
λmax	: Peak spectral sensitivity

LIST OF TABLES

Page

LIST OF FIGURES

Page

A NOVEL APPLICATION OF SMART HUMAN CENTRIC LIGHTING WITHIN THE SCOPE OF ENERGY EFFICIENCY AND COMFORT ASSESSMENT CRITERIA

SUMMARY

This study investigates the impact of human centric lighting (HCL) in an open plan office environment at Istanbul Technical University. The research involved sixty participants in the first phase and twenty-four in the second phase. The primary objective was to evaluate individualized lighting solutions that comply with Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) metrics. During the first phase, single Correlated Color Temperature (CCT) Light Emitting Diode (LED) sources were used, while the second phase explored the effects of different CCTs. Preliminary findings indicated potential for energy-efficient lighting modifications, with phase two concentrating on optimizing lighting quality and ensuring comfort criteria were met.

In the design development phase, the lighting design process was thoroughly outlined, including summaries of circadian lighting metrics, simulation tools, energy considerations, and the research plan for the circadian lighting open plan office. The study ensured that the design aligned with recommended thresholds for EML and CS, maintaining horizontal and vertical illuminance levels consistent with recommendations from the Illuminating Engineering Society (IES) for visual tasks.

Based on the simulation study, two different light distribution curve luminaires, Direct Suspended Linear (L1) and Direct and Indirect Suspended Linear (L2), were chosen for the study. Additionally, threshold suspended mounting heights of 1.5m (L1) and 2.3m (H3), and one Optimum Luminaire Height (OLH) of 1.8m (L2) above the finished floor were defined for the lighting luminaires. The experimental aspect involved assessing changes in lighting levels, psychological comfort, and performance at three main target heights (H1, H2, H3) for both lighting scenarios (L1 and L2). Participants were asked to complete visual cognitive performance tests, proofreading tasks, and the Karolinska Sleepiness Scale (KSS) test across six different lighting scenarios during the first phase to assess the impact of lighting level changes on psychological comfort, and four different lighting scenarios during the second study phase. The experiment aimed to explore human-centered lighting conditions alongside physiological comfort conditions, using questionnaires (Q1 and Q2) to gather data on error quantities (E) and time periods (t) as measurement scales, alongside participants' preferences based on their comfort criteria. Key results indicated that participants' performance and visual perception varied significantly across different lighting conditions and heights. The performance evaluation compared participants' results between heights H1, H2, and H3 for both L1 and L2 scenarios. Significant p-values indicated differences in performance and psychological comfort based on lighting levels, luminaire positions, and light distribution beams. Notably, the performance of participants was significantly influenced by age, with distinct differences observed between age groups 20-30, 30-40, and above 40.

Phase one of the study evaluates the lighting mounting height for human-centered lighting. A single CCT of 3800K was investigated to determine its influence on visual comfort and visual test responses. The scenarios of L1H3 and L2H2 were identified as the most successful. The most favorable scenario was observed in L1H3, both in terms of performance and participant preferences. Conversely, the results for L2H2 indicate that while participant performance was successful, their preference was lower compared to L2H3. Although L2H3 was preferable, L2H2 was selected for evaluation in phase two with CCTs of 2700K, 3800K, and 6000K.

Phase two of the study focused on varying CCTs to investigate their influence on visual comfort and circadian response. L1 was assessed with a constant CCT of 3800K, while L2 examined CCTs of 2700K, 3800K, and 6000K, set at operation rates of 75%, 60%, and 40% of the total luminaire output, respectively. These configurations aimed to meet the minimum CS requirement of 0.3. Regarding EML values, L1 had an EML set at 358, while L2 exhibited varied results: 275.5 for 2700K, 293 for 3800K, and 319 for 6000K.

The findings from phase two indicated dissatisfaction with the lighting set at 6000K, while warmer CCTs of 2700K likely had a positive impact due to the lower dimming rate meeting CS and EML requirements, resulting in higher illuminance levels on the desk compared to 3800K and 6000K scenarios. Participants clearly preferred higher heights (H3) for appealing lighting conditions, confirming the strong correlation among subjective evaluations of lighting scenarios such as color pleasantness, lighting satisfaction, and lighting heights.

Overall, the study suggests that individualized lighting systems tailored to open plan office environments can enhance worker satisfaction and meet HCL requirements. Using consistent survey questions across different lighting concepts can help identify specific factors influencing CCT preferences. In conclusion, integrating individualized lighting systems in open plan offices aligns with HCL requirements, ensuring worker satisfaction and potentially improving performance. The findings provide insights for enhancing office lighting environments, emphasizing the importance of considering both energy efficiency and occupant comfort.

ENERJİ VERİMLİLİĞİ VE KONFOR DEĞERLENDİRME KRİTERLERİ KAPSAMINDA AKILLI İNSAN ODAKLI AYDINLATMA UYGULAMASI

ÖZET

Akıllı aydınlatma sistemlerinin potansiyel faydaları çok yönlüdür ve en önemlisi de enerji tasarrufu sağlamalarıdır. Bu alandaki çalışmaların çoğu, verimli çalışan Işık Yayan Diyot (LED)'lerle maksimum enerji tasarrufu sağlanması üzerine odaklanmaktadır. Bu enerji tasarruflu akıllı aydınlatma sistemleri, güç tüketimlerinin azaltılma potansiyelleri yüksek olan, farklı kişilerin gün boyunca uzun saatler çalıştığı ofis binalarında sıklıkla uygulanmaktadır. İç mekanlarda akıllı insan odaklı aydınlatmanın (HCL) geliştirilmesinin, enerji tüketimi üzerinde olumlu etkiler yaptığı ve konfor kalitesini insan fizyolojisine bağlı olarak arttırdığı iddia edilmektedir.

Bu araştırma, açık plan bir ofis alanında elektrikli yapay aydınlatma tasarımını derinlemesine inceleyerek, çalışanların verimliliğini ve performansını artıran optimal insan merkezli aydınlatma tasarımı geliştirmeyi amaçlamaktadır. Çalışmada, Doğrudan Işık Yayan Sarkıt Lineer (L1) ve Doğrudan ve Dolaylı Işık Yayan Sarkıt Lineer (L2) olmak üzere iki farklı ışık dağıtım eğrisine sahip armatürler seçilmiştir. Özellikle, yapay aydınlatma tesisatları ile yaratılan düşey aydınlatma seviyeleri dikkate alınarak, tipik bir açık plan ofiste Sirkadiyen Uyarım (CS) ve Eşdeğer Melanopik Lüks (EML) değerlerinin belirlenmesine odaklanılmıştır. Görsel testler ve anketler dahil olmak üzere simülasyonlar ve deneysel ölçümler gerçekleştirilerek ofis çalışanlarının konfor tercihleri için optimal senaryoların belirlenmesi amaçlanmıştır. Bu çalışma, İstanbul Teknik Üniversitesi'nde açık ofis ortamında düzenlenmiş deney düzeneği ile HCL'nin çalışanlar üzerindeki etkilerini ve kişilerin tercihlerini araştırmaktadır. Araştırmanın birinci aşamasında altmış, ikinci aşamasında ise yirmi dört ofis çalışanı olabilecek potansiyeldeki deneklerle testler gerçekleştirilmiştir. Ana hedef, CS ve EML ölçütlerine uyan bireyselleştirilmiş aydınlatma çözümlerini değerlendirmektir. İlk aşamada aynı Renk Sıcaklıklı (CCT) LED ışık kaynakları kullanılmış, ikinci aşamada ise farklı CCT'lerin etkileri incelenmiştir. Enerji verimli aydınlatma değişiklikleri için potansiyel olduğunu gösteren ön bulgulardan sonra ikinci aşamada aydınlatma kalitesinin optimize edilmesi ve konfor kriterlerinin sağlanması üzerine odaklanılmıştır.

Tasarım geliştirme aşamasında, aydınlatma tasarım süreci, sirkadiyen aydınlatma ölçütleri, simülasyon araçları, enerji değerlendirmeleri ve sirkadiyen aydınlatma açık ofis araştırma planı ayrıntılı olarak açıklanmıştır. Çalışmada, EML ve CS için önerilen eşiklerle uyumlu bir tasarım gerçekleştirilerek, Aydınlatma Mühendisliği Topluluğu'nun (IES) önerileriyle tutarlı yatay aydınlık düzeyleri (EH) ve düşey aydınlık düzeylerinin (EV) sağlanması esas alınmıştır.

L1 ve L2 aydınlatma armatürlerinde 3800K CCT değerli LED ışık kaynakları kullanılarak ofis çalışanları için gerekli EH ve EV seviyelerinin sağlanması amacıyla bir simülasyon metodolojisi uygulanmıştır. Dinamik armatür montaj yüksekliği EV'e göre değerlendirilmiştir. Simülasyonlar, açık plan ofis için DIALux Evo tasarım programı ile elde edilen veriler Microsoft Excel ile analiz edilerek gerçekleştirilmiştir. Yatay aydınlık düzeyleri, bitmiş zemin seviyesinden 0,8 metre yükseklikte, 0,8×1,3 metre boyutlarındaki çalışma düzlemleri için hesaplanmıştır. Ayrıca, göz seviyesi ve bakış yönü ile uyumlu olarak bitmiş zemin seviyesinden 1,2 metre yükseklikte EV değerleri de hesaplanmıştır. Çalışma düzlemindeki EH ve deneğin göz seviyesindeki EV değerleri, L1 ve L2 aydınlatma armatürlerinin ışık yayan yüzeylerinin bitmiş zemin seviyesinden H1:1,5 metre, H2:1,8 metre ve H3:2,3 metre yükseklikte olmaları halleri için değerlendirilmiştir.

Deneysel aşamada, her iki aydınlatma armatürü (L1 ve L2) ve üç farklı yükseklik (H1, H2, H3) değerlerinde sağlanan aydınlatma seviyelerinin, deneklerin psikolojik konfor ve performansları üzerindeki etkileri incelenmiştir. Katılımcılardan, ilk aşamada aydınlatma seviyelerindeki değişimlerin psikolojik konfor üzerindeki etkisini değerlendirmek için altı farklı aydınlatma senaryosunda görsel karşılaştırma performans testleri, düzeltme testleri ile Karolinska Uykululuk Skalası (KSS) testini yapmaları istenmiştir. Deney, fizyolojik konfor koşullarıyla birlikte insan odaklı aydınlatma koşullarını belirlemeyi amaçlamış ve hata miktarları (E) ile zaman dilimleri (t) gibi ölçüm ölçekleriyle birlikte katılımcıların konfor kriterlerine dayalı tercihlerinin irdelenmesi için anketler (Q1 ve Q2) yapılmıştır.

Farklı aydınlatma seviyeleri, armatür pozisyonları ve ışık dağılım eğrileri ile elde edilen sonuçlar Minitab istatistiksel programı kullanılarak analiz edilmiştir. Katılımcıların performansı ve görsel algısı arasında cinsiyet, göz bozukluğu ve yaş faktörleri korelasyonları için L1H1 Q1'de p değeri 0,04, L1H1 Q2 E'de p değeri 0,03, L2H2 Q1 t'de p değeri 0,02, L2H2 Q2 E'de p değeri 0,04, L2H2 Q2 t'de p değeri 0,01, L1H3 Q2 t'de p değeri 0,02 olarak bulunmuştur. Ayrıca, L1H2 Q1 E göz bozukluğu p değeri 0,01 olarak bulunduğu için yaş ve göz bozukluğunun katılımcıların performansı üzerinde etkili olduğu da gözlemlenmiştir.

Katılımcıların performans değerlendirme sonuçları, farklı H1, H2 ve H3 yükseklikleri için karşılaştırılmıştır. L1 için H1 ve H3 Q1 t'de p değerleri 0,024, H1 ve H3 Q2 t'de 0,012, H2 ve H3 Q2 t'de 0,011 olarak bulunmuştur. L2 için ise H1 ve H2 Q1 E'de p değeri 0,028, H1 ve H3 Q2 E'de 0,008, H2 ve H3 Q2 E'de 0,036 olarak bulunmuştur. Bu p değerleri, L1 ve L2'nin farklı yüksekliklerindeki varyasyonlarına ilişkin performans farkı olmadığı savını reddetmektedir.

Bu sonuç göz önüne alınarak farklı H1, H2 ve H3'te L1 ve L2'nin performans farkının etkisi değerlendirilmiştir. P değerinin 0,05'ten düşük olarak bulunduğu test sonuçlarına göre, L1H1, L2H1 ve L1H2, L2H2'deki Q1 cevaplama sürelerinde ve Q2'de anlamlı farklar bulunmuştur.

Katılımcıların performans sonuçlarının farklı L1 ve L2 aydınlatma armatürleri için karşılaştırılması sonucunda, anlamlılık düzeyinin H1 ve H2 için Q1 t ve Q2 t'de reddedildiği, ancak H3 için onaylandığı gösterilmiştir.

P değerinin 0,05 olarak bulunduğu aydınlatma seviyelerindeki değişikliklere dayalı olarak performans ile cinsiyet ve görsel bozukluk arasındaki ilişki değerlendirilmiş, ancak anlamlı bulunmamıştır. Buna karşılık yaş faktörü, özellikle 20-30 ve 30-40, 20-30 ve 40 ve üzeri yaş grupları arasında aydınlatma seviyelerindeki değişikliklere dayalı olarak performans ile anlamlı bir ilişki göstermiştir.

Aydınlatma seviyelerinin yeterliliği subjektif olarak değerlendirilirken, kullanıcılar L1H1 ve L2H3'ü tercih etmişlerdir. Test sonuçlarına göre ise, L1H3 ve L2H2 en uygun senaryolar olarak değerlendirilmiştir. Işık dağılım eğrileri farklı olan aydınlatma armatürlerinden L1 düzeneği her üç farklı armatür yüksekliğinde de daha yüksek oranda tercih edilmiştir. Test sonuçları, algılanan aydınlatma seviyelerindeki farklılıkların kişisel psikolojik konfor izlenimlerini etkilediğini göstermiştir. Daha yüksek aydınlık düzeyleri değerleri gibi fiziksel konfor koşullarındaki iyileştirmeler olumlu olarak değerlendirilmiştir. Gerçekleştirilen tüm senaryolarda hem L1 hem de L2'de düzgünlük sağlanmış, ancak L2H2'de aydınlatmanın düzgünlüğü diğer senaryolara göre daha düşük seviyede kaydedilmiştir.

Bu tez çalışmasının sonuçlarına göre, "aydınlatma seviyelerinin artırılması performansı artırır" şeklinde genel bir çıkarım yapılamamaktadır. Test sonuçları, L1H3 ve L2H2'nin deneklerin performansları açısından en başarılı senaryolar olduğunu göstermektedir. L1H3 senaryosunda EH: 752,5 lux, EV: 550 lux ve L2H2 senaryosunda EH: 520 lux, EV: 393 lux olup, her iki durumda da minimum CS ve EML değerleri sağlanmaktadır.

Memnuniyet açısından, katılımcılar en yüksek memnuniyeti L1H3 ve L2H3 senaryolarında ifade etmişlerdir. Diğer yandan, L1H3 ve L2H2'de yüksek performansın elde edilmiş olması bu çalışmanın ilginç bir bulgusu olarak değerlendirilmektedir. H2 yüksekliğinde, hem L1 hem de L2 aydınlatma düzeneklerinde %40 enerji tasarrufu önerilebilmektedir. Ancak, ışık dağılım eğrisi ve armatürlerin SPD'sine bağlı olarak önerilen enerji verimli aydınlatma senaryosu, minimum CS ve EML değerleri sağlanması için L1H3 senaryosunda göz ardı edilmiştir. Öte yandan, L2H2'de başarılı bir performans kaydedilmiş olmasına rağmen, katılımcıların memnuniyet yorumları düşük olmuştur. Ofis çalışanlarının performansı, test sonuçlarında kaydedildiği gibi yaş gruplarına büyük ölçüde bağlıdır. Bu yorumlar, L1H3'teki performans durumu ile de uyumludur, ancak bu senaryoda enerji tasarrufu söz konusu değildir. L2H3'te memnuniyet oranı daha yüksekken, katılımcılar L2H2'de daha iyi performans göstermiş ve bu senaryo enerji verimliliği açısından da öne çıkmıştır. Sonuç olarak, L1H3 ve L2H2 senaryolarında, çalışma düzlemlerinde aydınlık düzeyleri ve düzgünlük yeterli olmasına rağmen, katılımcı memnuniyeti düşük kalmıştır.

Çalışmanın ikinci aşamasında, deney düzeneğinde CS'in minimum 0,3 değerinde olması esas alınarak zeminden 2,3 metre yükseklikteki (H3) L1 aydınlatma armatürü 3800K renk sıcaklığında %100 ışık akısı oranında çalıştırılmıştır. Yine aynı yükseklikteki L2 aydınlatma armatürü ise 2700K, 3800K ve 6000K renk sıcaklıklarında, sırasıyla %75, %60 ve %40 ışık akısı oranlarında çalıştırılmıştır. L1 düzeneğinde EML: 358 olarak ayarlanmış, L2'de ise 2700K için EML: 275,5, 3800K için EML: 293 ve 6000K için EML: 319 sonuçları elde edilmiştir. Tez çalışmasının bu bölümünde, ofis ortamında değişken CCT'lerin görsel konfor ve sirkadiyen yanıt üzerindeki etkisinin araştırılması amaçlanmıştır.

Katılımcıların farklı aydınlatma seviyeleri ve ışık spektrumlarının yaratıldığı aydınlatma tesisat kombinasyonlarına verdikleri yanıtlar incelenmiştir. Bu bağlamda, ofis çalışanı olarak tanımlanan yirmi dört katılımcı, görsel performans testlerini tamamlamış ve dikkat, çevresel memnuniyet ve uyku hali ile ilgili değerlendirmeler yapmıştır.

Çalışmanın ikinci aşamasının bulguları, bazı ofis çalışanlarının 6000K renk sıcaklıklı aydınlatmadan memnuniyetsizlik duyduğunu göstermektedir. Dimleme oranlarının CS ve EML gereksinimlerini karşılayacak düzeyde tutultuğu 2700K gibi daha sıcak CCT'ler, katılımcılar üzerinde olumlu bir etki yaratmıştır. Bu senaryoda, 3800K ve 6000K renk sıcaklıklı senaryolara kıyasla çalışma masası üzerinde daha yüksek aydınlık düzeyleri sağlanmıştır.
L1H3 3800K ve L2H2 2700K arasında p değeri 0,002 olan anlamlı korelasyonlar gözlemlenmiştir. Benzer şekilde, ışığın rengi konusunda, L1H3 3800K ve L2H2 3800K arasında p değeri 0,024 ve L2H2 3800K ile L2H2 6000K arasında p değeri 0 olan anlamlı korelasyonlar bulunmuştur. Aydınlatmadan memnuniyetsizlik konusunda da, L2H2 3800K ve L2H2 6000K arasında p değeri 0 ve L2H2 2700K ile L2H2 6000K arasında p değeri 0,016 olan anlamlı korelasyonlar gözlemlenmiştir. Ayrıca, aydınlatma armatür yüksekliği tercihleri konusunda L1H3 3800K ve L2H2 2700K, L2H2 3800K ve L2H2 2700K, L2H2 3800K ve L2H2 6000K arasında sırasıyla p değeri 0,038, 0,044 ve 0 olan anlamlı korelasyonlar hesaplanmıştır.
Bu bulgular, katılımcıların H2'ye kıyasla daha yüksek olan H3'ü tercih ettiklerini göstermektedir. Bu çalışmanın bir başka önemli bulgusu da, farklı aydınlatma senaryolarında aydınlatma yükseklikleri, ışık renk sıcaklıkları gibi parametreler ile aydınlatma memnuniyeti arasında güçlü bir korelasyon gözlemlenmiş olmasıdır.
Tez çalışmasının sonuçlarına göre, açık ofis ortamlarına uyarlanmış bireyselleştirilmiş aydınlatma sistemlerinin çalışan memnuniyetini artırabileceği ve insan odaklı aydınlatma (HCL) gereksinimlerini karşılayabileceği önerilebilmektedir. Sonuç olarak, açık ofislerde bireyselleştirilmiş aydınlatma sistemlerinin entegrasyonu, HCL gereksinimlerini karşılayarak çalışan memnuniyetini sağlamakta ve potansiyel olarak çalışma performansını artırmaktadır. Bu yöntem ile çalışanların konforu dikkate alınarak, enerji verimli çözümler elde edilmesi de olanaklıdır.

1. INTRODUCTION

Intelligent systems play an important role for indoor applications. The development of smart lighting technique consists of two main stages which improves energy saving performance. The first step is to replace the conventional light sources with new technology light emmited diodes (LEDs). In addition, LEDs are used as the dominant light source for lighting and, focuses on improving the performance of LEDs for higher efficiency, getting cheaper cost and longer lifetime are the advantages of the LEDs. The second stage of the development of intelligent lighting is the lighting control algorithm, and adaptive lighting as an important advantage that it is much easier to adjust the luminous flux and colour temperature values of LEDs to different values compared to convential light sources. Indeed, entegreted Human Centric Lighting (HCL) has the goal of this phase to ensure that the smart lighting system has higher performance in efficiency, and meets users' comfort requirements. Light is fundamental to human life, enabling interaction with the environment through visual perception. It allows people to perceive details in spaces, buildings, and surroundings. Visible light, spanning from 380nm to 780nm, constitutes a narrow band of the electromagnetic spectrum. The use of light in buildings has been examined from various perspectives, including architectural, aesthetic, and functional considerations. Furthermore, light plays a crucial role in a building's environmental impact, with electrical lighting usage significantly influencing overall energy consumption. The role of lighting design is defined by the function of the building, such as offices, where creating a healthy and productive environment is paramount. Recent researches have highlighted the impact of the 446-583nm range on human health, directly and indirectly [1]. This spectrum, characterized by blueish color shades, influences the human biological system, including circadian rhythms. Circadian rhythms govern the human sleep cycle, recurring every 24.2 hours as a biological clock regulated primarily by light. Insufficient changes in light can disrupt this clock, leading to desynchronization an effect known as the non-visual effect of light. As a result, numerous studies investigate how light affects human health and develop methods to measure its non-visual effects. New metrics, such as Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML), have been recently developed for this purpose. However, there is currently no internationally agreed standard for these metrics, which strongly rely on vertical light illuminance (EV) rather than the conventional horizontal iluminance (EH) on working planes. Limited research has focused on assessing vertical illuminance in spaces and its impact on building occupants.

1.1 Purpose of Thesis

The potential benefits of smart lighting systems are versatile, the most important of which is the increased energy savings. As a result, most of the work in this field is currently focused on achieving maximum energy savings with LEDs operating efficiently. These energy-saving smart lighting systems are often installed in office buildings where different people work long hours throughout the day, as they have the highest potential to reduce power consumption. Therefore, with the advancement of intelligent indoor HCL it affects industrial, commercial applications positively on energy consumption and increasing comfort quality depends on human physiology.

This research aims to delve deeply into electrical artificial lighting design in an open-plan office space to develop an optimal human centered lighting design enhancing occupants' productivity and performance. It will specifically concentrate on studying vertical illuminance from artificial electric light and determining the CS value and EML value across a typical open-plan office. This study aims to determine optimal scenarios for office workers' comfort preferences, employing simulations and experimental measurements, including visual tests and surveys.

1.2 Literature Review

HCL has garnered attention as an innovative lighting design approach for buildings in recent years [2]. Over the past two decades, researchers have explored light's impact on health in office settings [3]. Recent advancements in technology and a deeper understanding of physiological responses have prompted a reevaluation of studying light's influence in real-life settings [4]. Circadian effectiveness, often used synonymously with the potency of light in eliciting positive, non-visual responses in humans, involves various physiological and behavioral reactions mediated by retinal photoreceptors [4, 5, 6, 7]. The goal is to develop indoor lighting solutions that dynamically adapt to occupants' physiological and biological needs, promoting positive human outcomes like improved sleep, health, and well-being [8]. Unlike traditional lighting systems focused solely on visual acuity, HCL considers light's profound impact on human physiology, cognition, and emotions [9, 10]. Research has demonstrated potential benefits of HCL across various building types, including offices, healthcare facilities, educational institutions, and residential spaces [11]. For example, properly designed HCL systems can enhance employee productivity and satisfaction in office environments, improve patient outcomes in healthcare settings, and support student performance and well-being in educational facilities. Implementing HCL effectively requires consideration of factors such as timing, intensity, and spectral characteristics of light, integrating architectural design, lighting control systems, and occupant preferences [12, 13]. However, challenges persist in terms of standardization, cost-effectiveness, and occupant acceptance. Ongoing research and advancements in lighting technology are driving the adoption of HCL in building design and operation. To measure circadian lighting effects, metrics like CS and EML are commonly used, quantifying how light affects the body's circadian system [14, 15]. These metrics consider light intensity and spectral composition that stimulate melanopsin receptors in the eyes, crucial in regulating sleep-wake cycles. The CS metric assesses light's effectiveness in suppressing melatonin through a complex model of human phototransduction [16, 17]. Understanding lighting's impact on alertness, sleep, and occupant satisfaction is crucial for maintaining a healthy office environment [18, 19, 20]. Limited research exists on lighting's non-visual effects in real office environments, but studies highlight the potential for improved alertness through proper lighting application [21, 22, 23].

[24] mentions that during the winter phase of their study, exposure to high morning illuminance was linked to significantly shorter sleep durations based on sleep diary data, and another study found that participants reported decreased perceived sleep quality after exposure to tunable lighting, with objective sleep quality progressively declining over the study period, resulting in an average reduction of 24 minutes in deep sleep duration [25]. Studies focusing on daylight revealed that participants in windowless offices scored lower in two dimensions of the Short Form 36 Health Questionnaire (SF-36) and reported poorer overall sleep quality compared to those in

offices with windows [26]. Additionally, individuals in office spaces equipped with electrochromic glazing slept an average of 37 minutes longer than those in spaces with traditional blinds mostly closed [27]. Figueiro et al. reported significantly higher sleep quality and duration during the summer compared to the winter study period [9], and seasonal variations significantly influenced the phasor angle, a measure of circadian entrainment [28]. Measures related to stress, mood, and vitality were included in 17 instances across all studies; however, significant findings were primarily associated with factors other than lighting conditions. [25] found no significant effects on multiple subjective and objective stress measures. [29] observed a higher need for stress recovery among participants in January compared to February and March. In a subsequent study, these authors identified subjective fatigue, prior sleep duration, prior social engagement, and prior physical effort as predictors of subjective vitality, in addition to hourly light exposure [30].

Its found that participants reporting higher general health, vitality, and mental health on the SF-36 also generally reported being more alert, with participants exhibiting greater sleepiness at the start of the week [31]. A significant correlation between the amount of light and subjective alertness was observed for 6 out of 46 participants based on EH measurements, and notably, providing saturated red light from a desktop luminaire reduced participant sleepiness at 3 p.m. [32], and improved alertness was reported in the afternoon during dynamic lighting conditions compared to static lighting [25]. Additionally, participants exposed to high morning illuminance levels reported significantly higher daytime sleepiness than those with low morning light exposure [24].

Apart from the effects on alertness and sleep, understanding occupant perceptions and satisfaction with various lighting conditions proposed to produce these effects is crucial. Hence, [29] found no significance related to alertness, vitality, or sleep quality; however, participants expressed a preference for dynamic lighting conditions. [33] discovered that CCT played a significant role in participant perception compared to light output. Participants rated 5000K conditions as brighter but associated with greater visual discomfort, lower satisfaction, and reduced self-reported productivity. Furthermore, participants' "lighting beliefs" changed significantly after the study, with agreements on statements like "Visually cool light makes me uncomfortable" and "Bright, harsh fluorescent light makes me feel tense".

The impact of lighting characteristics (e.g., spectrum, intensity) on the perception of architectural environments is likely complex and context-dependent. Although widely used, CCT only predicts the appearance of a light source based on models of human color vision [34] and does not account for circadian entrainment primarily driven by the melanopsin photopigment [35, 36].

Therefore, it's important to acknowledge the limitations of current knowledge on lighting [37]. While we have a good understanding of how light impacts our visual capabilities and perceptions, there is still no consensus on these topics due to variations in psychophysical studies. As for the non-visual effects, we speculate that many aspects of the human body are affected by light, yet these areas remain relatively unexplored. Therefore, as emphasized by numerous researchers [37, 38, 39, 40], comprehensive lighting research encompassing both visual and non-visual domains is still required.

1.3 Hypothesis

In the study, the change in comfort conditions in office environments devoid of the influence of daylight, depending on different lighting scenarios, is investigated. Parameters providing 'comfort' conditions, it is defined as 'physiological comfort' and 'psychological comfort'. In an experimental setup where physiological comfort conditions and, the change in psychological comfort conditions is investigated depending on the positioning of the light source and the luminaire with two different light distribution curves. Six different lighting scenarios at phase 1 in a single CCT and four scenarios at phase 2, were created with three different lighting scenarios with the same luminaire types for each in an experimental setup designed in accordance with the layout of a single person working desk, where the entry of daylight from the windows is prevented. The system allows the luminaires to be dimmed with the remote control, dynamic height, fixed at different light levels and the variables in the study can be searched for each scenario. The comfort parameters measured in the experimental setup are investigated for the luminaire height, CCTs and Spectral Power Density (SPD) type conditions of the only variable, respectively. Performance measurements are investigated based on the CS and EML standard ratios of the lighting. In the study, visual comfort conditions are researched for the luminous level and the recommended CS, EML based on the two newest standards. As the comfort condition investigated, the light distribution curve of luminaires and the height at which they are positioned are variable; the light color temperature, the position of the furniture in the space and the dimensions of the space are kept constant at phase 1 of the study. While examining the comfort conditions measured in the study, phase 2 is completed in order to examine the preference of the office workers for variable CCTs. The parameters that are kept constant are the luminaires, furnishing elements in the space are office dimensions and reflection ratios.

2. NON VISUAL EFFECT OF LIGHTING

The understanding of how lighting affects human well-being has undergone significant advancements in recent years. Rather than being seen as purely functional, light is now recognized as a crucial element that influences our physical, mental, and emotional states. This recognition has given rise to a new approach in lighting design as HCL.

HCL focuses on creating lighting environments that prioritize the well-being and needs of individuals. It acknowledges the profound impact of light on our bodies and our internal circadian rhythm, which regulates important biological processes like sleep-wake cycles, hormone production, mood, alertness, and cognitive performance. Light, including its intensity, color temperature, and timing, plays a vital role in synchronizing and regulating these rhythms.

Traditionally, artificial lighting has often been static and unable to provide the necessary light stimuli to support our natural biological rhythms. However, the advent of LED technology has revolutionized the industry and paved the way for the development of HCL. LED lighting offers advantages such as energy efficiency, longer lifespan, and precise control over lighting parameters.

With the help of LED technology, HCL can replicate or simulate natural lighting conditions, thereby positively impacting our health, well-being, and productivity. HCL systems have the ability to dynamically adjust the color temperature and intensity of light throughout the day, imitating the progression of natural daylight. This means providing brighter, cooler light in the morning and afternoon to enhance alertness and productivity, while transitioning to warmer, softer light in the evening to facilitate relaxation and prepare for sleep. Beyond the regulation of sleep-wake cycles, HCL has been found to have additional benefits, including mood enhancement, stress reduction, improved cognitive performance, and even supporting certain medical treatments. As a result, HCL has found applications in various settings such as workplaces, educational institutions, healthcare facilities, and residential spaces.

Implementing HCL requires a collaborative and interdisciplinary approach. Researchers, architects, lighting designers, manufacturers, and engineers work together to develop new concepts, measurement strategies, and lighting solutions that optimize human well-being. This involves gaining a deeper understanding of the complex photoreceptive inputs and non-visual responses to light, establishing guidelines for effective lighting design, and creating intelligent lighting control systems that can adapt to individual preferences and environmental conditions.

While HCL is still an evolving field, its potential to enhance our daily lives and well-being is unquestionable. By acknowledging the profound impact of light and harnessing advanced lighting technologies such as LEDs, HCL aims to create indoor environments even outdoor, that promote health, productivity, and overall well being. The advent of LED lighting has improved relationship of light and human body system. Light is a powerful stimulus for regulating circadian, behavioral and hormonal systems. Additionally, light therapy is effective for certain disorders, sleep problems, circadian rhythm disruption, and productivity.

The biological and behavioral effects of light are influenced by a distinct photoreceptor in the eye, melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs). New concepts of light measurement strategy and tricks taking account to the operation of complex photoreceptive inputs to the non-visual responses which are suggested to use by researchers architectural lighting designers, lighting manufacturers, and engineers.

Therefore, it is important that non-visual effects of light should be included into considerations for lighting designs. After all, to answer the question, what extent is given architectural lighting replicates the biological effects of natural daylight; how lighting could be employed to minimize the unfavorable effects of tasks like shift works while improving alertness and safety; moreover, improving alertness of office workers and students at classrooms or how light therapy could be optimized. To clarify the details, it’s important not only to know the updates about eyes undiscovered aspects, but also the knowledge and the story behind it. The fact is proposing an effective indoor lighting, improves occupants performance while spending time at the place. Moreover, it helps to provide an energy efficient lighting system. Here are the details of eye and photoreceptors that help to evoke non-visual effect of light in human body.

2.1 The Eye

The eye is a significant and intricate organ that captures electromagnetic radiation from the environment. It undergoes a process called phototransduction, transforming this radiation into electrical signals. These signals are then relayed to the lateral geniculate nucleus (LGN) in the brain via the optic nerve, facilitating visual perception. Phototransduction primarily takes place in the retina, a small structure located in the innermost layer of the eye. The majority of the eye is filled with fluid, which includes aqueous humor in the front portion and vitreous humor in the larger, interior portion. Aqueous humor supplies nutrients to the cornea and lens, while vitreous humor helps maintain the eye's shape and clear any obstructions that could impede incoming light, as illustrated in Figure 2.1. [41].

Light enters the eye and undergoes refraction by both the cornea and the double-convex crystalline lens, which work together to focus the light onto the surface of the retina. While the lens does not possess the same refractive power as the cornea, it can finely adjust to sharply focus light from different distances. To focus light from distant objects onto the retina, the lens flattens, while for closer objects, it thickens and becomes more rounded due to the action of the ciliary muscle surrounding the lens. Figure 2.1 depicts a simplified illustration of the eye's structure, demonstrating how light enters and swiftly traverses through its various sections before being interpreted by the brain.

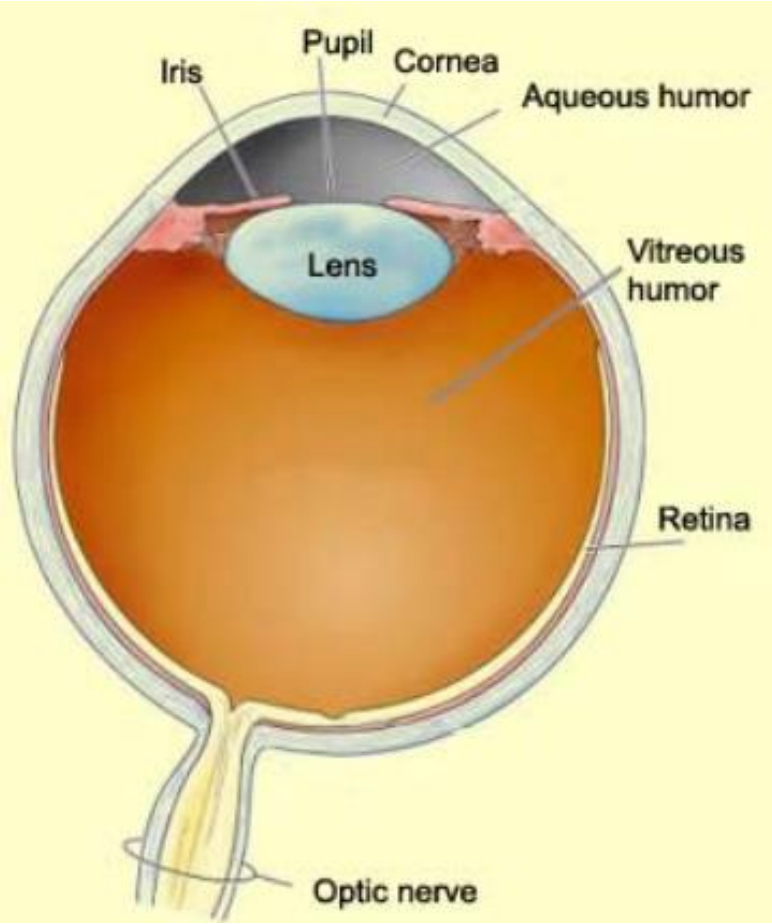


Figure 2.1: In the simplest terms the eye [41].

2.2 The Retina

The retina, an extension of the brain, consists of three main layers housing five types of neurons, as illustrated in Figure 2.2. The outer nuclear layer, which contains photoreceptors (i.e., rods and cones); The inner nuclear layer, which houses bipolar, horizontal, and amacrine cells; The ganglion cell layer; Intervening structures: the outer plexiform layers; Intervening structures: inner plexiform layers; The outer and inner plexiform layers facilitate connections between the three aforementioned layers of cells.

The human retina exhibits inversion, with photoreceptors situated in the farthest layer from where light enters the eye. Upon reaching the photoreceptor layer, light is absorbed by the "classical" photoreceptors, namely rods and cones. Any light not absorbed by the photoreceptors is captured by the pigment epithelium, located at the rear of the retina behind the photoreceptors. This arrangement prevents light from being reflected back in the direction it originated from [42].

The photoreceptors transmit signals to the bipolar cells, facilitated by the horizontal cells, while the bipolar cells relay signals to the ganglion cells with the assistance of the amacrine cells. Ultimately, visual information is conveyed via the axons of the ganglion cells, which traverse the nerve fiber layer at the forefront of the retina. These axons converge at the optic disk, forming the optic nerve responsible for transmitting signals to various targets in the brain [43]. The operation of eye while light enters and pass through it is shown with details of layers in Figure 2.2.

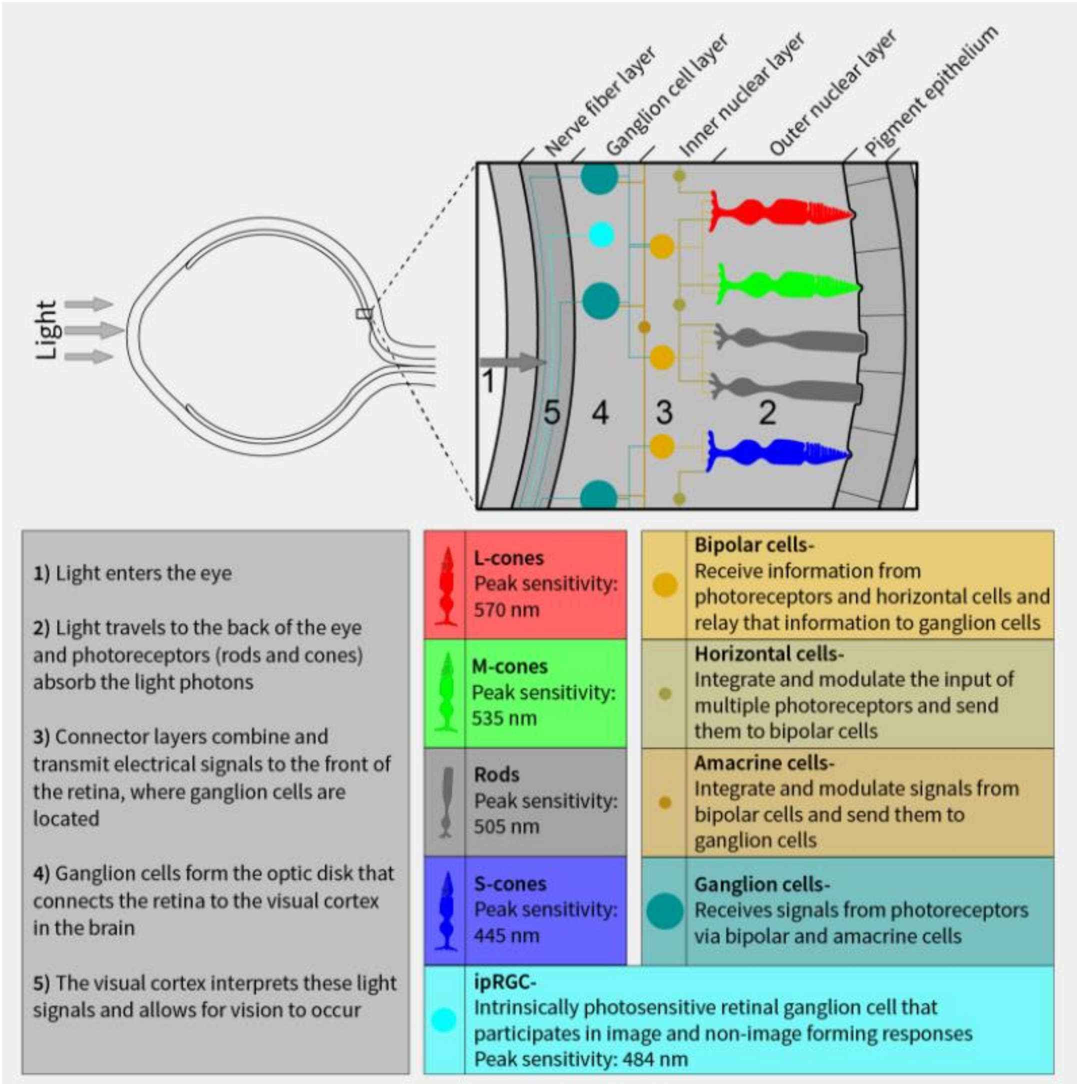


Figure 2.2: The retina in details [42].

2.3 Spectral Sensitivity

The ipRGC firing signal, which initiates physiological and behavioral responses to light, is determined by the collective impact of several photoreceptive processes. These processes include the melanopsin-driven phototransduction mechanism within the ipRGC itself, as well as distant photoreception occurring in rods and cones Figure 2.3 (B) [44]. Each of these mechanisms for detecting light possesses a unique spectral sensitivity, determined by the spectral efficiency of the expressed photopigment and the spectral transmission properties of the ocular media. All classes of retinal photoreceptors play a role in regulating circadian, neuroendocrine, and neurobehavioral responses to light. As illustrated in Figure 2.3 (A), which depicts the relevant retinal circuitry in humans, non-image-forming responses originate in the retina and are associated with a specific class of ipRGCs. These ipRGCs exhibit direct photosensitivity due to the expression of melanopsin, enabling them to respond to light even when isolated from the rest of the retina. When connected to the outer retinal rod and cone photoreceptors via conventional retinal circuitry, their intraretinal connections are not fully understood and likely vary among different subtypes [44].

Illustrated here are the primary connections, with on cone bipolar cells (on CBCs) linking them to cone photoreceptors, and via amacrine cells (AII) and rod bipolar cells (RBC), to rod photoreceptors. Consequently, the firing pattern of ipRGCs can be influenced by both intrinsic melanopsin photoreception and extrinsic signals originating in rods and each of the spectrally distinct cone classes (depicted in red, green, and blue). This concept is represented in a simplified manner as multiple photoreceptive mechanisms (designated as R for rod opsin; M for melanopsin; SC for S cone opsin; MC for M cone opsin; and LC for L cone opsin), each absorbing light based on its individual spectral sensitivity profile (illustrated as plots of log sensitivity against wavelength from 400 to 700 nm) to generate a distinct measure of illuminance. These five input signals are then amalgamated through retinal wiring, and within the ipRGC itself, to produce an integrated signal that is transmitted to non-image-forming centers in the brain. [44]. Since each of the five representations of weighted irradiance is generated by a photopigment with its distinct spectral sensitivity profile, their respective importance for the integrated output determines the wavelength dependency of this signal, and consequently, of downstream responses.

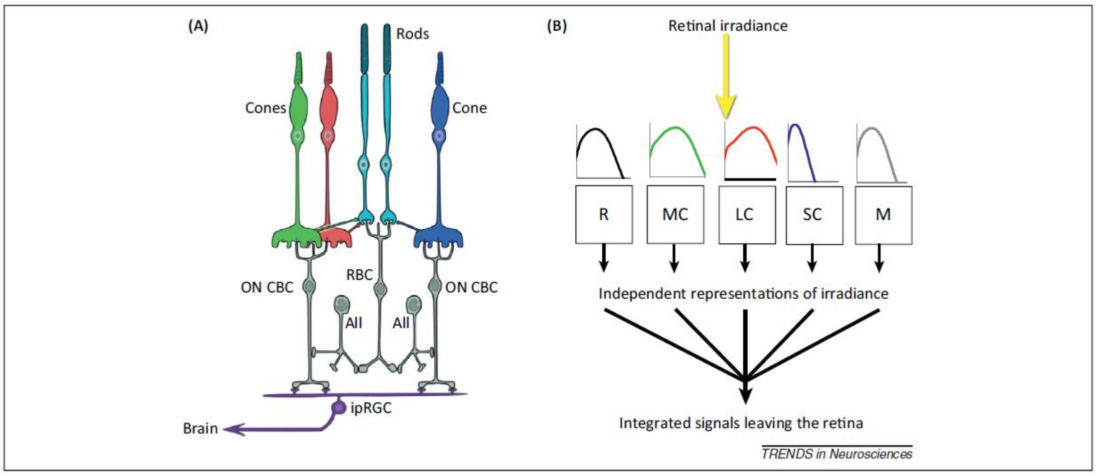


Figure 2.3: A. Schematic of the relevant retinal circuitry in humans. Retinal ganglion cell (ipRGC), on cone bipolar cells (on CBCs), amacrine cells (AII) and rod bipolar cells (RBC), rod photoreceptors, rods and cone classes (shown in red, green and blue). B. A number of photoreceptive mechanisms depicted as R for rod opsin; M for melanopsin; SC for S cone opsin; MC for M cone opsin; and LC for L-cone opsin, each of which absorbs light according to its own spectral sensitivity profile [44].

Rods, Cones, Melanopsin are summarized as below, to understand the main role in observing the nonvisual effects.

Rod opsin, the photopigment of rod photoreceptors, shows peak sensitivity (λmax) at approximately 500 nm in all mammalian species. In humans because of filtering the standard human observer peak sensitivity is at 507 nm.

Cones, mammalian genomes typically contain several genes encoding spectrally distinct cone opsins. Humans, and other old-world primates, have three types of cones. Human S cones express a short wavelength sensitive cone opsin (cyanolabe), maximally sensitive to wavelengths at ~420 nm; M cones contain a different cone opsin (chlorolabe; peak sensitivity ~535 nm); L cones contain a red-shifted cone opsin (erythrolabe; peak sensitivity ~565 nm) [43]. In humans, kind of filtering shifts peak sensitivity of short- and medium-wavelength cones to longer wavelength (~440 and ~545 nm, respectively).

Melanopsin, the available data indicate that the spectral sensitivity of melanopsin, the photopigment of ipRGCs, is similarly invariant across species, with λmax at approximately 480 nm [45].

It would be desirable to be able to quantify light as experienced by non-visual systems using a single, one-dimensional unit such as the equivalent of photopic lux. Achieving this for lights of divergent spectral content, however, needs to be explained of a suitable spectral weighting function. Evoked responses reflect input from all the retinal photoreceptor classes, with the relative importance of each being highly labile within and between response types. As a result, the spectral sensitivity of this photoreceptive system is fundamentally context dependent.

3. MEASURING METHODS FOR IPRGC-INFLUENCED RESPONSES TO LIGHT

Biological photoreceptors exhibit varying sensitivities to different wavelengths of light. Photometry techniques address this inherent challenge by employing methods that consider the spectral sensitivity of the biological system being studied. These techniques often utilize mathematical or optical filters to prioritize the energy at each wavelength according to the system's spectral sensitivity.

The traditional visual receptors, rods and cones, are relatively well understood and characterized in existing publications by the International Commission on Illumination (CIE). However, groundbreaking research conducted over the past 25 years has revealed the existence of another type of photoreceptor in the eye, which plays a crucial role in the non-visual effects of light. These photoreceptors, known as ipRGCs, exhibit peak sensitivity in the shorter wavelength range of the visible spectrum. As discussed earlier, ipRGCs rely on the photopigment melanopsin contained within them for their intrinsic photosensitivity.

For measuring the nonvisual effect of light on humans a very update CIE 2018 S26 standard had published. The background of the standards stands on the [42] study, much accurately.

3.1 CIE S 026/E:2018

CIE System for Metrology of Optical Radiation for ipRGC influenced responses to light is published in year 2018 and based on the theory that explained in [46]. This standard emphasizes the non-visual impacts of light, which are contingent upon factors such as spectral power distribution, spatial distribution, timing, and duration of light exposure. It accounts for individual-specific parameters, such as an individual's circadian phase and history of light exposure. The relationship between these variables and the actual physiological responses to light can then be examined using established light measurement concepts, which do not rely on observing subjective responses from individuals. Moreover, this standard incorporates details regarding the effects of age and field of view when quantifying retinal photoreceptor stimulation for light responses influenced by ipRGCs [46]. It is better to be noted that this International Standard does not give complete information for lighting applications, or for the quantitative prediction of ipRGC-influenced responses. The standard mentions opsin-based photopigment of human eye photoreceptor, and responses are denoted by the symbol α, besides its characteristics in the context of ipRGC-influenced responses to light that α in the term indicates one of five different photoreceptor responses which are shown in Figure 2.3 and explained in spectral sensitivity part.

S-cone-opic; relating to the human S-cone response due to its photopigment.

M-cone-opic; relating to the human M-cone response due to its photopigment.

L-cone-opic; relating to the human L-cone response due to its photopigment.

Rhodopic; relating to the human rod cell response due to its photopigment.

Melanopic; relating to the human ipRGC response due to its photopigment.

Human photoreceptors are defined with α-opic, that are listed with reference to the CIE standard. The α-opic that are listed in CIE S 026/E:2018 to explain mathematical way for evaluating the non-visual effect of light [47]. The approach outlined in CIE S 026/E:2018 establishes standard action spectra for all five recognized photoreceptors in the human eye, delineating their roles in influencing responses to light mediated by ipRGCs. Utilizing CIE S 026/E:2018 to assess the effects of non-visual light on humans involves simplifying Melanopsin Metrology, thereby providing a practical method for applying the standard. For melanopic normalization, the spectral response of photoreceptors needs to be quantified using melanopic effective watts. Melanopic effective watts are presently defined similarly to photopic lumens, but with the substitution of the melanopic sensitivity function normalized to unity at its peak wavelength sensitivity of 490 nm [48]. Melanopic effective watts are defined Figure 3.1. and explicitly equation by (3.1):

$$M(S) = \int S(\lambda)M(\lambda)d\lambda \tag{3.1}$$

where S(λ) is the SPD of the source, M(λ) is the melanopsin sensitivity function

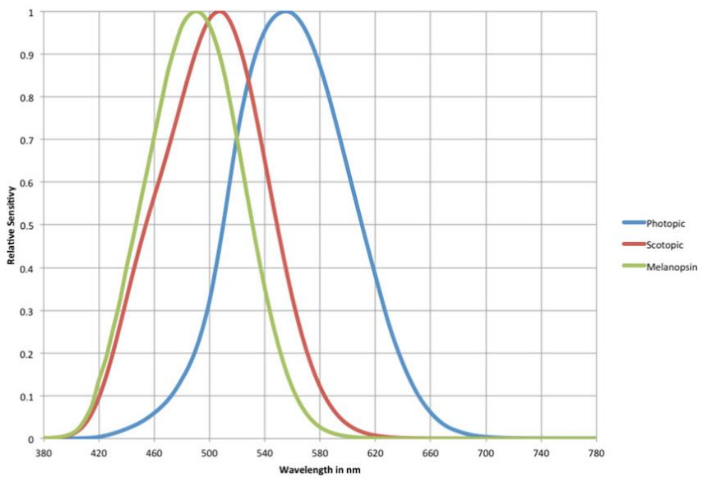


Figure 3.1: Spectral sensitivity curve for melanopsin (green line), with the scotopic and photopic curves shown for comparison [48]. The melanopsin function is taken from [48].

3.2 Equivalent Melanopic Lux Modelling

The EML metric is a photometric quantity derived from the relative spectral sensitivity of melanopsin, it is a proposed alternate metric that is weighted to the ipRGCs instead of to the cones, which is the case with traditional illuminance level (lux). During Performance Verification, EML is measured on the vertical plane at eye level of the occupant. For this purpose, melanopic ratio (MR) calculator is suggested to evaluate the EML for the occupants. The calculator had announced by International Well Building Institute [49] to simplify the measurements of none visual effects of light. Figure 3.2 shows the form of the MR Calculator [50]. The SPD of the luminaire must be inserted to user colums at the Data sheet of the [50], selecting a built-in sample source or a user-entered source at Data sheet of the [50]. For user data, paste luminaire SPD (5 nm increments) into User1 or User2. Next, on the Circadian sheet of the Excel file, select User1 or User2 as the source that has been populated with SPD data. Then, the melanopic ratio appears. Multiply the melanopic ratio by the measured or modeled vertical illuminance to calculate the equivalent melanopic lux.

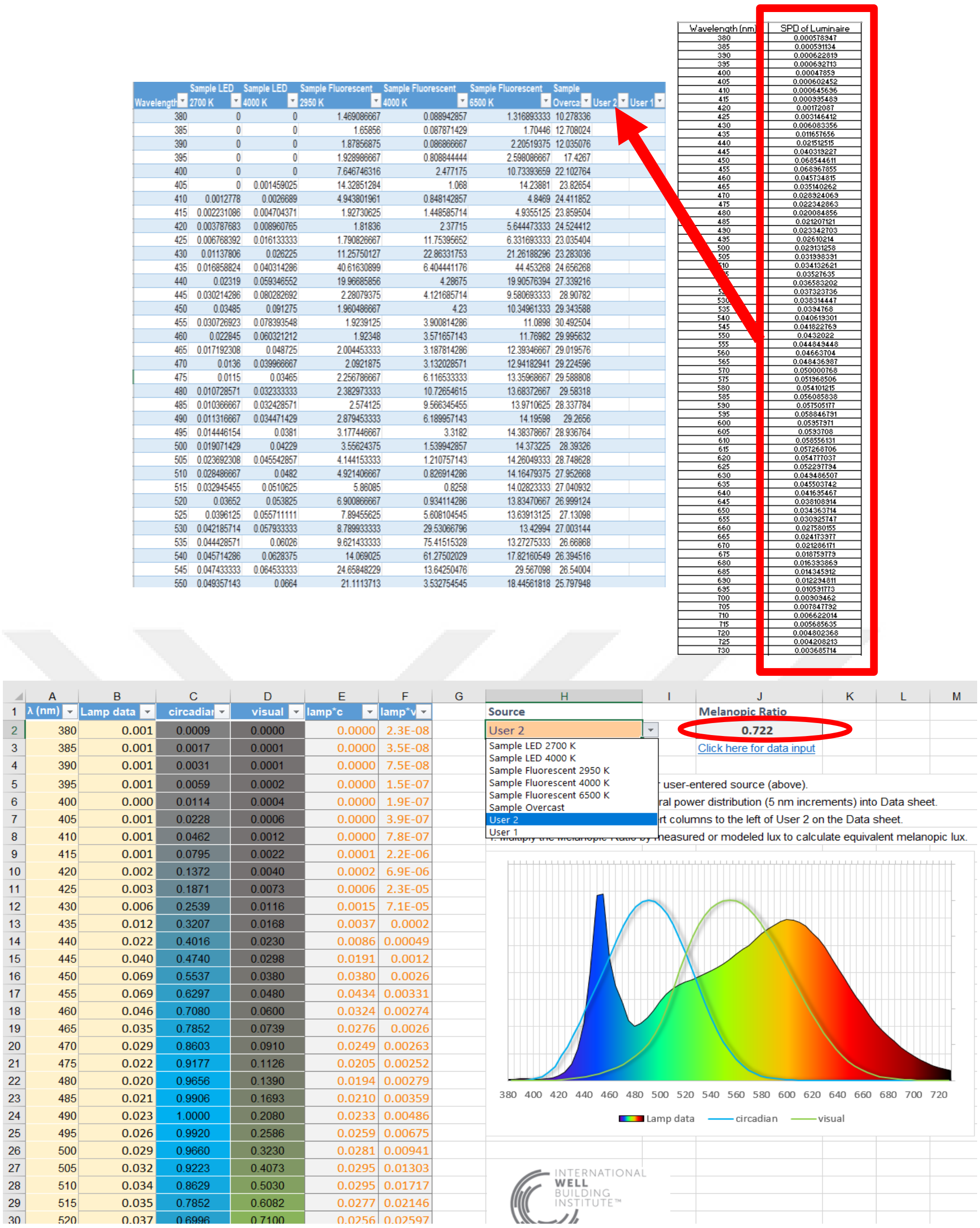
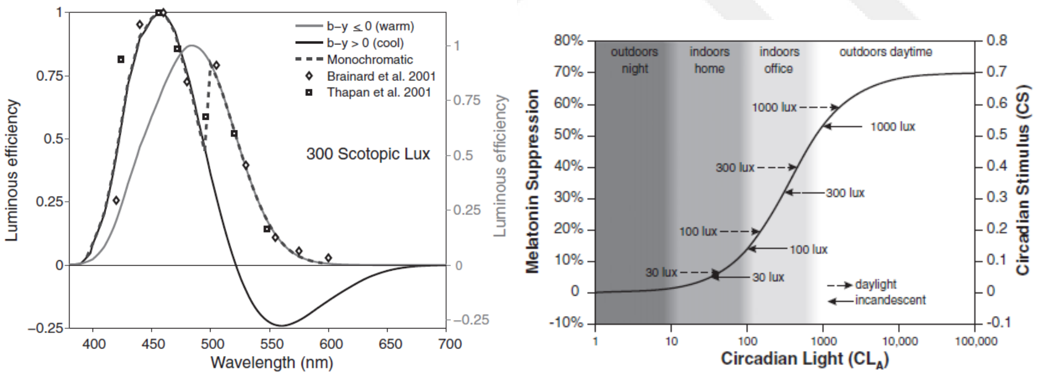


Figure 3.2: EML Ratio Calculator [50]

To operate the calculator, luminaire Spectral Power Density (SPD) should be inserted to User columns, then the relative EML ratio pops up. To measure EML, EML ratio should be multiply to the EV, that access the occupant cornea to get the EML amount. Moreover, well standards proposed satisfied EML levels for different indoor concepts which should be carry out in lighting designs [49].

3.3. Circadian Stimulus Lux Modelling

This model is also based on fundamental knowledge of retinal neurophysiology and neuroanatomy, including the operating characteristics of circadian phototransduction (converting light into electrical signals), from response threshold to saturation [51]. The ipRGCs are the central elements in the phototransduction model, consistent with electrophysiological and genetic knockout studies [52]. The model also reflects neural input from the outer plexiformlayer of the retina, consistent with studies showing that signals from rods and cones provide photic information to the ipRGCs [51]. Using this phototransduction model, the spectral irradiance at the cornea is first converted into Circadian Light CL_A which is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the response of the biological clock, based on nocturnal melatonin suppression. CL_A, and then, transformes into the CS, reflecting the absolute sensitivity of the circadian system. Thus, CS is a measure of the effectiveness of the retinal light stimulus for the human circadian system from threshold (CS: 0.1) to saturation (CS: 0.7) [13,14]. Figure 3.3 shows the absolute sensitivity of the human circadian system plotted as a function of CL_A [15].



(A) (B)

Figure 3.3: (A) The light source causes blue versus yellow spectral opponent channel (b-y) to signal “yellow” (ie, for a warm light source), the spectral sensitivity is defined in terms of the photopigment melanopsin. The b-y channel signals “blue” (ie, for a cool light source), the spectral sensitivity is defined in terms of melanopsin plus the short-wavelength sensitivity (S)-cone. (B) The modeled absolute sensitivity of the human circadian system based upon nocturnal melatonin suppression. [50]

The corresponding values for photopic illuminance, CL_A, and CS for common light sources (incandescent and daylight) are shown in Figure 3.3 The following equations show how CL_A and CS are determined [52].

$$CL_A = \begin{cases} 1548\left[\int Mc_\lambda E_\lambda + \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d_\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{Rodsat}}\right)\right)\right] & \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda D\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda > 0 \\ 1548 \int Mc_\lambda E_\lambda D\lambda & \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \leq 0 \end{cases} \quad (3.2)$$

Where:

CL_A circadian light. The constant, 1548, sets the normalization of CL_A so that 2856K blackbody radiation at 1000 lux has a CL_A value of 1000.

Eλ light source spectral irradiance distribution

Mcλ melanopsin (corrected for crystalline lens transmittance)

Sλ S-cone fundamental

mpλ macular pigment transmittance

Vλ photopic spectral sensitivity function

V′λ scotopic spectral sensitivity function

RodSat half-saturation constant for bleaching rods = 6.5W/m2

k = 0.2616

ab-y=0.7000

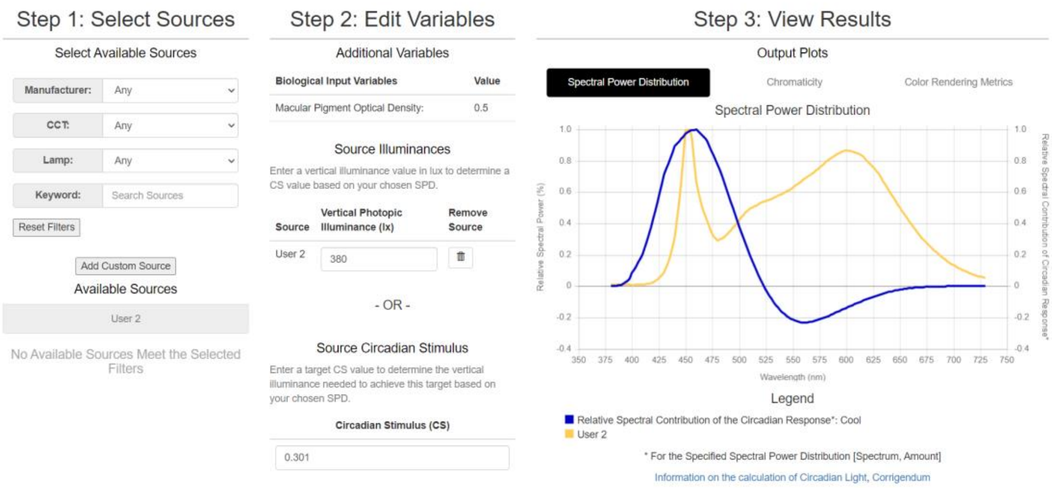
arod=3.3000

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}} \quad (3.3)$$

The model has been successfully used to predict the effectiveness of various light sources and spectra for activating the circadian system in laboratory [53, 54, 55] and in field studies. One issue that the presence of daylight in a building does not necessarily insure high CS exposure for workers. Most of the buildings studied here were designed to maximize daylight availability in the space, yet CS exposures did not always reach the desired criterion level of 0.3. Furniture placement, window shade positions, desk space locations and orientations, and visual and thermal comfort need to be taken into consideration when attempting to maximize exposure to CS in an office environment [15]. Although the scientific evidence clearly shows that the response by the circadian system involves all types of photoreceptors, and not just the ipRGC response, designers may still be required to provide minimum EML at the eye if they are compelled to comply with the Well Building Standard. The EML metric has been adopted as the metric of choice for that standard because it is calculated using a relatively straightforward method, but EML is incomplete in the sense that it does not take into account the contribution of the classical photoreceptors, or spectral opponency, in circadian phototransduction [56, 57]. Nonetheless, for lots of the light sources an EML was always associated with a CS. With a few exceptions, which can be explained by the non-linearity of the CS model due to spectral opponency, an EML between 200 and 250 was associated with a CS of 0.25 or greater. Measuring CS is practical while using the Lighting Research Center Calculator [58], it is important to know the best target for the place and using the SPDs of the exact luminaire and mentioned factors to access the right non-visual lighting design.

Figure 3.4 shows a sample calculation of the CS [58]. First, the SPD data are manually inserted into the source section. Then, after selecting the inserted data, the measured EV must be entered into the Vertical Photopic Illuminance (lux) section. The CS value then appears in the box.

(A) (B)



(C)

Figure 3.4: A: Shows the sample calculation platform of CS. B: source section that SPD data are manually inserted into. C: After the inserted EV, the CS value is calculated in the box [58].

4. STUDY DESIGN OF HUMAN CENTERED LIGHTING FOR OPEN PLAN OFFICE

For over two decades, researchers have dedicated their efforts to exploring the effects of light in office environments. Recent technological advancements and a deeper understanding of physiological responses have prompted a reevaluation of the approach to studying light's impact in real-life settings. This study aims to observe how occupants in actual office settings respond to human-centered lighting, while considering its effects on comfort criteria.

Circadian effectiveness is a term often used to describe the ability of light to elicit positive non visual responses in humans. These non-visual responses encompass circadian, neuroendocrine, and neurobehavioral reactions mediated by signals from the retinal photoreceptors, including rods, cones, and ipRGCs. To measure circadian effectiveness in lighting, two key metrics are employed: CS and EML, as defined in CIE S 026:2018. The most commonly used metrics for assessing circadian lighting effects include EML is measured in m-lux, CS is dimensionless, and the more recent Melanopic Equivalent Daylight Illuminance (M-EDI, measured in lux). These metrics involve applying distinct response functions to the light spectrum and incorporating light intensity as a scaling factor. Both EML and M-EDI are based on the melanopic response of intrinsically photosensitive retinal ganglion cells, which are most sensitive at 480 nm. The primary difference between the two metrics lies in the reference sources used: equal energy for EML and D65 for M-EDI. They can be easily converted between each other using a simple scalar multiplier (EML $\approx$ M-EDI $\times 1.103$).

The CS metric, on the other hand, assesses light's effectiveness in suppressing melatonin through a more complex model of human phototransduction. This model integrates data from experiments on human nocturnal melatonin suppression and factors in estimations of rod and cone photoreceptor responses. For this purpose, the most suitable and effective luminaire type is studied, with suspended luminaires demonstrating superior results compared to ceiling types [59-63]. Appendix A, Table

A.1 shows the detail information of the proposed luminaires for the open plan Office. Furniture arrangements also play a significant role because the EV is a crucial factor in meeting the requirements of CS and EML.

The study consists of two phase; phase 1 is study with 60 participant to clarify the important factors on proposed human centered lighting and phase 2 is completed with 24 participants for the clarifation of the effect of CCT differetion on participants Figure 4.1. shows the diagram of study procedure.

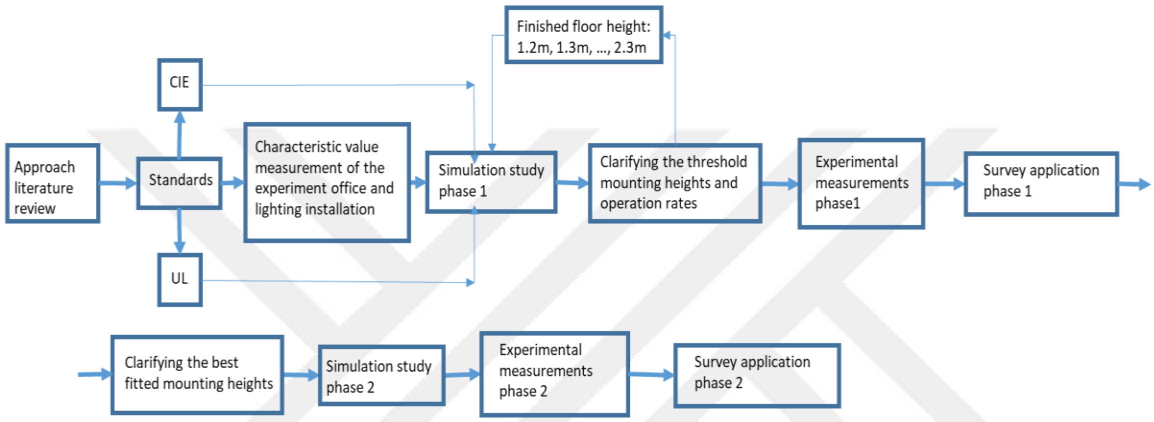


Figure 4.1: Diagram of study procedure.

4.1. Simulation and Experimental Study of Open Plan Office

After reviewing methodologies and science used in HCL researches, a computer simulation methodology is implemented to investigate different luminaire types with different curve distribution and multiple CCTs and different rate of operating due to compare in terms of circadian light for CS and MR for EML. Varying in the variables, needs computer simulation to choose the most appropriate methodology, it will give an advantage of controlling the variables, and it will save money and time since there are 10 luminaire scenarios that need to be tested. Computer simulation will guarantee faster and accurate results by avoiding human and instruments errors.

Luminaire types for office lighting should always be designed to meet the worker's requirements; selecting the luminaire type has a key role in defining the space atmosphere and light level. Moreover, multiple variables shall also be considered, such as; electrical powers (W) and luminous flux (lumen) values.

Regarding the simulation study on the five best-fitted luminaire selections listed in Appendix A. Table A.1 for offices, two best-fit luminaires (direct suspended linear and direct and indirect suspended linear) were selected based on high output results on CS, EML, and energy efficiency due to the lower quantity compared to others. The simulation study of the open-plan office lighting was completed to choose the optimum solution for human-centered lighting in open-plan offices. Furthermore, it is shown that the arrangement of the desks and the view direction of the office workers are important factors that cannot be ignored.

The CCT is ignoring to accept as variables that could affect circadian lighting in the Phase 1. To measure this effect, different illuminance level were evaluated according to the desired CS and EML for the samples listed in Appendix A. Table A.1 which shows the details of the selected luminaires to be studied in this research and the details of the luminaire in lighting design for the office with dimensions of 4.9×4.6×2.8 meters which is located in Energy Institute of Istanbul Technical University with geographic location of 41°06'27.7"N 29°01'50.9"E in target of working plane lighting on 0.8 height of room floor. The simulation model is conducted for open office Figure 4.2.

Figure 4.2: Sample open plan office at Istanbul Technical University.

Light curve distribution or light distribution curve gives useful information about the light, where designers and architects can select the best choice according to the space function and the light level required on the work plane. Regarding [60], There are five different types of light distribution curves available for luminaires that are suitable for use in office environments. Appendix A, Figure A.1 shows the luminaire placement and mounting grid for luminaire on Table A.2 as A, B, C, D, E, and shows detailed results of the lighting design for open plan office for an occupant desk.

Appendix A, Figures A.2-A.17, show the output of DIALux Evo, MATLAB, and Excel that were used for the simulation due to their reliability, flexibility in luminaire selection, and the ability to export detailed vertical illumination calculation data. It mentions three EH targets for the office: 300 lux, 500 lux, and 750 lux minimum at a height of 0.8 meters above the floor Table A.2. The importance of the arrangement is evident in the MATLAB 3D plots, as shown as a sample in Figure 4.3, which illustrate the vertical calculation surfaces for EV. To analyze how this lighting affects occupants, 3D plots were used to display the vertical illuminance values relative to the height and width of the office. The results of the vertical surface calculations reveal the EV value on the vertical calculation surface at a height of 1.2 meters from the finished floor, defining the eye level.

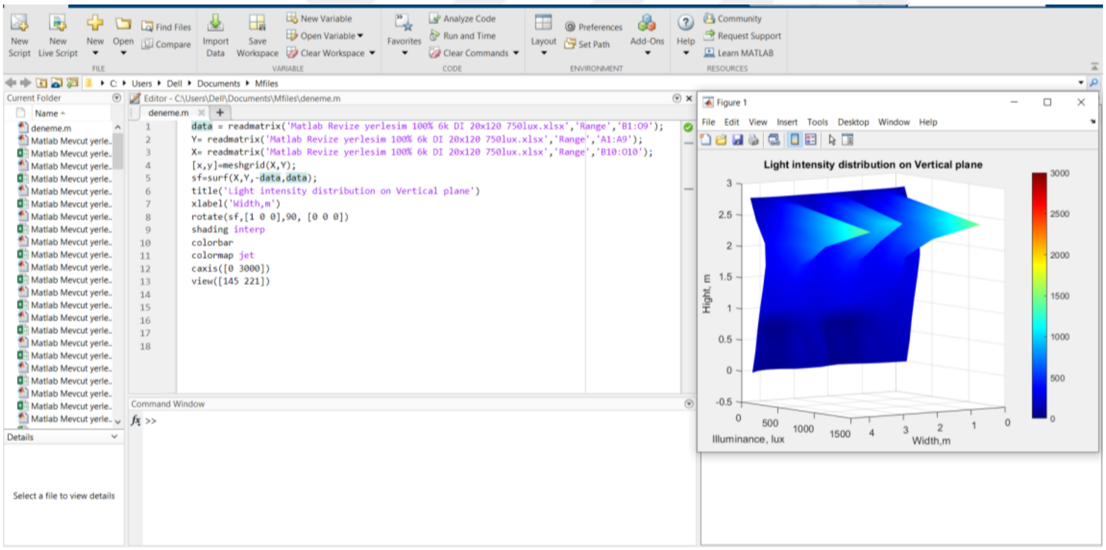
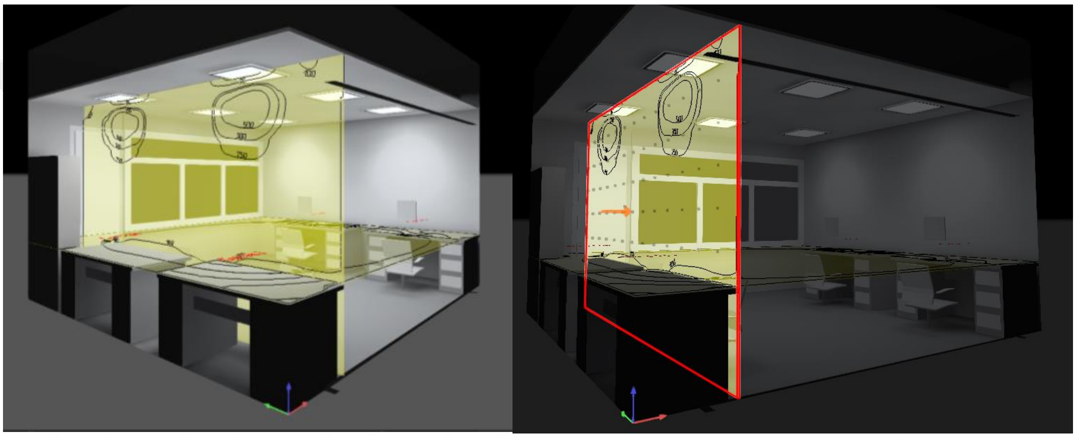


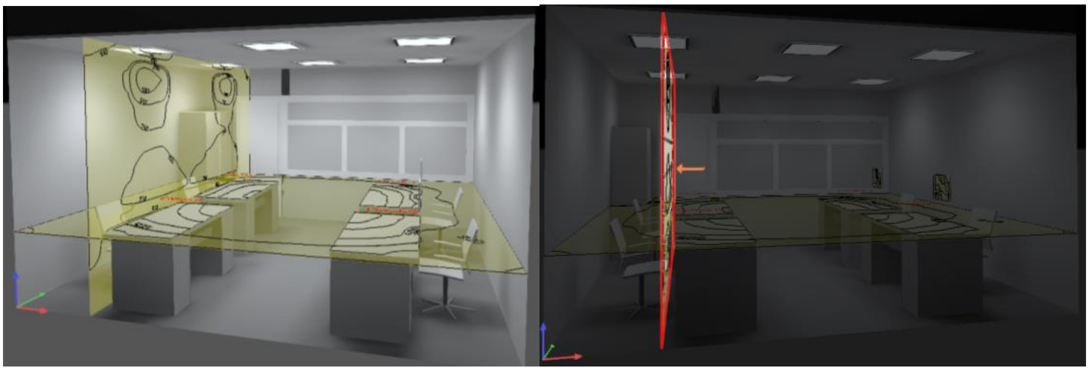
Figure 4.3: MATLAB script for 3D plot.

The calculation surfaces are used to measure illuminance levels in the space. A horizontal calculation surface, with desk dimensions of 0.78m×1.6m, is placed on the working plane at 0.8 meters above the finished floor level. The average level of EH is evaluated at a minimum of 500 lux for activities such as writing, typing, reading, and data processing, or a minimum target of 300 lux for tasks such as filing documents [64] and copying in the office. For tasks requiring greater accuracy, such as those in educational offices, a target of 750 lux is set.

The research had aimed to investigate the effect of vertical illuminance on occupants rather than focusing solely on the working plane. Therefore, vertical calculation planes were positioned according to the users' positions, covering the full height of the space. These planes are positioned to measure vertical illuminance values towards the users, considering both current and revised arrangements in the same office. Figure 4.4. (A) shows the vertical calculation surface direction and horizontal calculation surfaces for current office arrangement. (B), and the vertical calculation surface direction and horizontal calculation surfaces for revised suggested office arrangement.



(A)



(B)

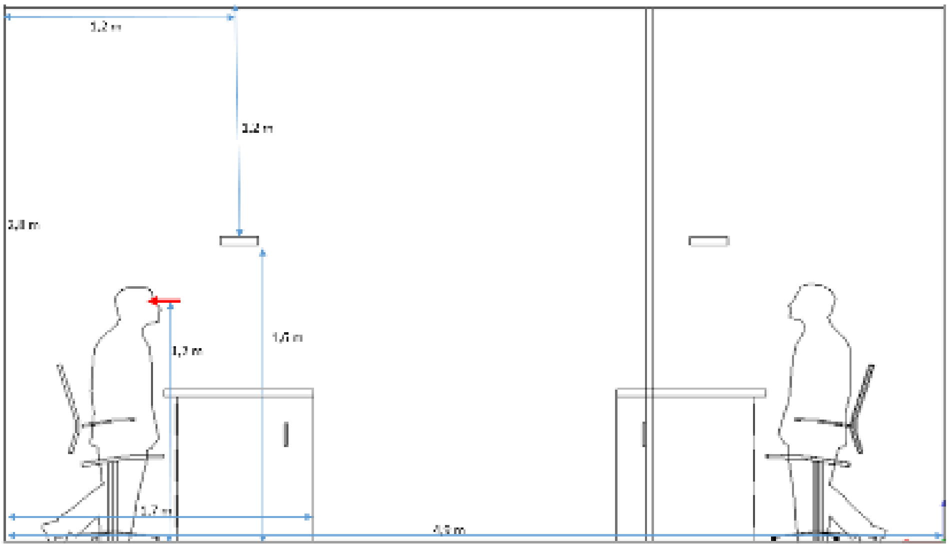
Figure 4.4: (A) The vertical calculation surface direction and horizontal calculation surfaces for current office arrangement. (B) The vertical calculation surface direction and horizontal calculation surfaces for revised suggested office arrangement.

In order to select the best type of luminaires, five different types were examined. Among the proposed luminaires, the best-suited ones, direct/indirect linear pendant lights and suspended linear lights were selected for installation in a mock-up setting. The mock-up setting was done by changing the direction of the desks of office workers to maximize the EV and, accordingly, the EML and CS values. Desks were set with a 1.2 meter distance from the back wall, and luminaires were installed at the top center of the desks. The luminaires were arranged to dynamically adjust their height in accordance with the furniture layout. Two types of single CCT suspended luminaires at 3800K were evaluated for lighting results regarding EV for office applications. The maximum CS and EML at eye level were considered optimal for determining the luminaire mounting height through theoretical calculations and practical experimentation. Notably, when comparing between luminaires, the EV at eye level increases with both the luminous flux output and the light distribution curve's effect on the vertical plane.

The computer simulation method was employed to assess the impact on circadian lighting in an open-plan office. The simulation model was configured to align with occupants' view angles on the X-axis (-30, 0, +30 degrees) and the Y-axis (90 degrees toward the center of the office), with the entire vertical plane covered to match the users' view direction. EV at the occupant's eye level was evaluated at each 10cm interval to identify the highest result, aiming to achieve higher CS and EML. Figure 4.5. A presents, 3D modeled for suggested arrangement for the same open office and B presents, schematic of the suggested arrangement for the same open office.

It is evident that vertical illuminance exhibits significant variations relative to height, indicating that even small changes in the observer's height can lead to notable shifts in vertical illuminance which are shown in Appendix A, Figure A.18-A.20, and SPDs of the luminaires are listed on Table A.3.

(A)



(B)

Figure 4.5: (A) 3D modeled for suggested arrangement for the same open office. (B) Schematic of the suggested arrangement for the same open office.

Heights were selected for the luminaires in the simulation to assess optimal outputs for office workers. Confirmation of the suspended luminaire was obtained, and the comparison rates of CS and EML are provided in [60] for the LINEAR SUSPENDED D/I and LINEAR SUSPENDED luminaires at operation rates of 20%, 50%, and 100%, across mounting heights of 1.3m, 1.4m, 1.5m, 1.6m, 1.7m, 1.8m, 1.9m, and 2m, as depicted in Figures 4.6, 4.7, 4.8.

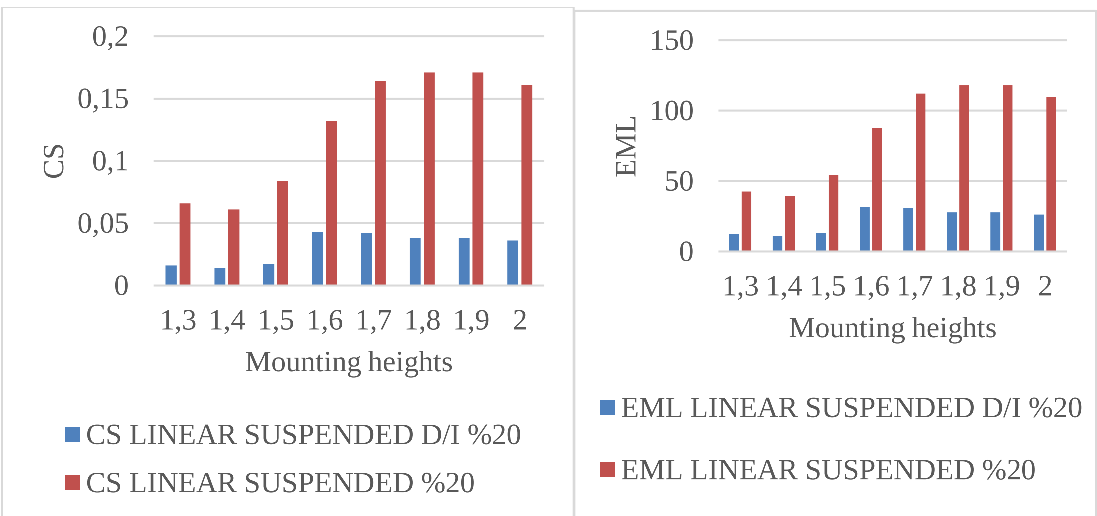


Figure 4.6: CS and EML Comparison of LINEAR SUSPENDED D/I %20 and LINEAR SUSPENDED %20 luminaire in heights of 1.3m, 1.4m, 1.5m, 1.6m,1.7m, 1.8m, 1.9m, 2m.

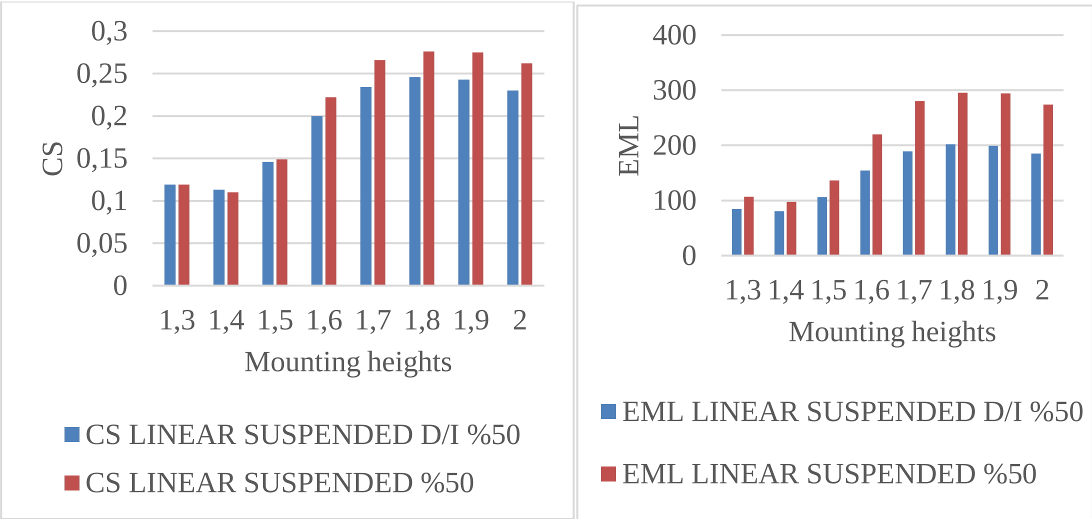


Figure 4.7: CS and EML Comparison of LINEAR SUSPENDED D/I %50 and LINEAR SUSPENDED %50 luminaire in heights of 1.3m, 1.4m, 1.5m, 1.6m,1.7m, 1.8m, 1.9m, 2m.

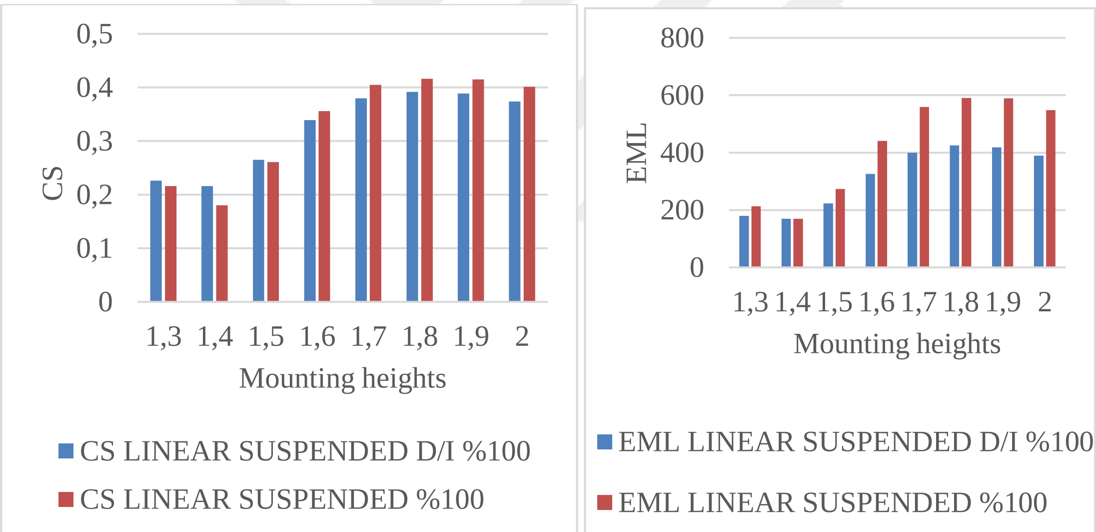


Figure 4.8: CS and EML Comparison of LINEAR SUSPENDED D/I %100 and LINEAR SUSPENDED %100 luminaire in heights of 1.3m, 1.4m, 1.5m, 1.6m,1.7m, 1.8m, 1.9m, 2m.

The results indicate that high power consumption of luminaires does not necessarily guarantee high EML and CS values. Therefore, the effectiveness of the light curve in directing light into the eye plays a crucial role in increasing CS and EML rates. The mounting height of the light source is dependent on the light beam, so evaluating the highest CS and EML amounts through examination with related software is essential. Experimental confirmation is also necessary to confirm the effect and comfort criteria. Figures 4.6, 4.7, 4.8 illustrate that the CS and EML outputs of the two suspended luminaires. The linear direct luminaire exhibits much more appealing results than the luminaire with direct and indirect light distribution curve.

Two organizations, the International WELL Building Institute (IWBI) and Underwriters Laboratories (UL), have established guidelines for incorporating the human circadian system into office lighting design. The WELL framework encompasses various environmental aspects and allows for earning certification points through design features, including the circadian lighting feature witch is feature aims to provide varying levels of EML [49]. Under UL Design Guideline 24480 (UL 2019) [65], guidelines are provided for creating and verifying circadian-effective lighting in offices, primarily using the CS metric. In addition to these circadian metrics, the lighting design takes into account the Illuminating Engineering Society (IES) guidelines [66] for color rendering and task illumination, including uniformity ratios. This study sets goals for both simulation design and experimental design.

The study consists of a simulation phase and a series of consecutive experiments conducted in an open-plan office. The main objective of these experiments is to investigate how different lighting conditions impact the overall experiences of office occupants. The CS metric, a physiologically relevant measure of circadian effectiveness in lighting outlined in UL 24480 [65], and the EML metric referred to in CIE S 026:2018 [67], serve as the corresponding evaluation schemes for the proposed Human Centered Lighting design. The targets for the study regarding UL 24480 and WELL v2 2023 Q2 which is based on CIE S 026:2018 is presented as recommended metric thresholds.

The selected office has dimensions of 4.9×4.6×2.8 meters and is located in the Energy Institute of Istanbul Technical University on the Ayazaga Campus, Maslak, Istanbul, Turkey, with a geographic location of 41°06'27.7"N 29°01'50.9"E. The lighting target is set at a working plane height of 0.8 meters from the floor. The measured reflectance values for the office are as follows: 40% for the floor, 90% for the walls, 90% for the ceiling, 2.5% for chairs, and 86% for desks and drawers. These values are used as input for simulation studies as well. The results of the study simulation design for the office are continuously monitored with experimental measurements conducted concerning the simulated results, aiming to confirm the statistical cases accordingly.

Regarding the standards, office workers are required to maintain a minimum CS of 0.3 during office hours and 0.4 during the highest productivity time zone (office hours). The study aims to achieve a CS of 0.3 in all scenarios. Additionally, the EML needs to surpass 275 to achieve a higher rank on the WELL v2 2023 Q2 target, earning 3 points toward WELL certification. To calculate the CS, the SPD of luminaires must be entered into the online calculator provided by the Lighting Research Center (LRC) [68]. This calculation is based on the EV of the occupant's line of sight in the office. Similarly, to determine the EML, the same SPDs are input into the MR calculator [50] to obtain the MR value for each individual luminaire.

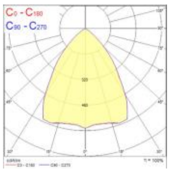
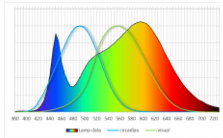
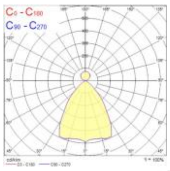
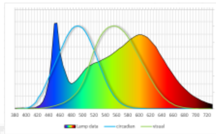
The SPDs of the luminaires were measured experimentally at the photometry and radiometry laboratory of the Energy Institute at Istanbul Technical University, covering wavelengths from 380 nm to 730 nm. The MR values calculated by the MR calculator indicate an MR of 0.722 for L2 and 0.651 for L1 lighting system. The evaluation of the desk's EH and the direction of EV at the occupant's eye level were performed at three different height steps: H1 at 1.5 m, H2 at 1.8 m, and H3 at 2.3 m above the finished floor. The distance from the wall behind the occupant was set at 1.2 m. These measurements were taken to achieve the target CS and EML levels, as shown in Table 4.1. Moreover, Figure 4.2 shows the details of the L1 and L2 with SPD characteristics at Figure 4.9, Appendix A, Table A.4.

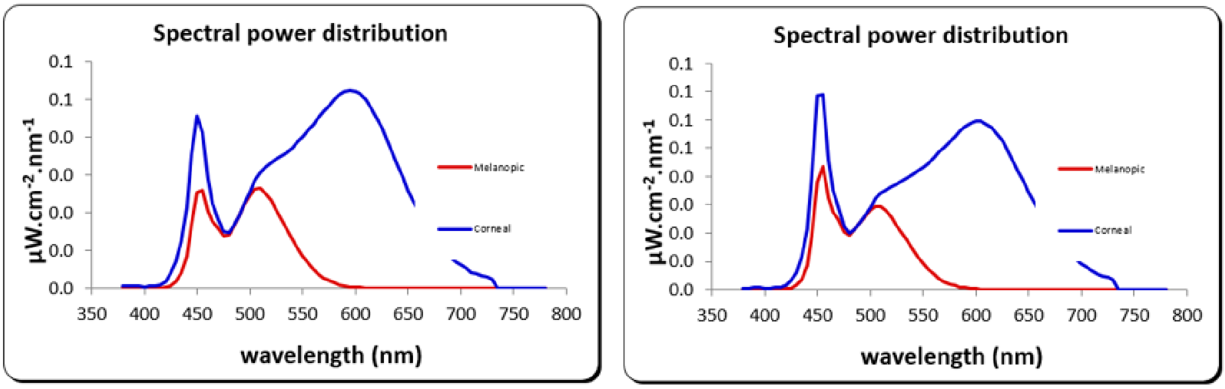
Regarding WELL Standard - V3 2020, illumination models or illumination calculations at least 250 EML is required at 75% or more of workstations, measured on the vertical plane facing forward, 1.2 m above finished floor on view of the occupant [69].

Table 4.1: Target of EML and CS regarding documentations

Documents	Recommendations
WELL v2 2023 Q2	EML ≥ 275 [250 M-EDI]
UL Design Guideline 24480 (2019)	CS ≥ 0.3

Table 4.2: L1 and L2 luminaires specification

Luminaire Name	Luminaire Photo	Light distribution curve	Total Power Consumption (W)	Luminous Flux (Lumen)	Correlated Color Temperature (K)	Melanopic Sensitivity Curve	MR
L1			27	2947	3800		0.651
L2			34	3315	3800		0.722



L1 L2

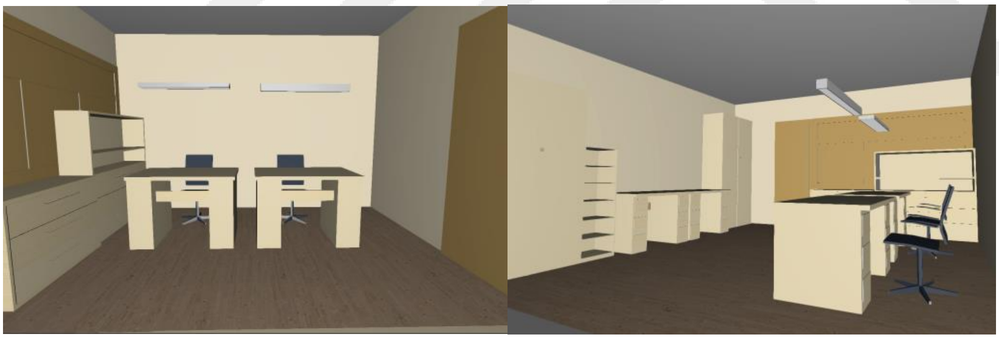
Figure 4.9: Spectral power density of L1 and L2.

4.1.1. Simulation study

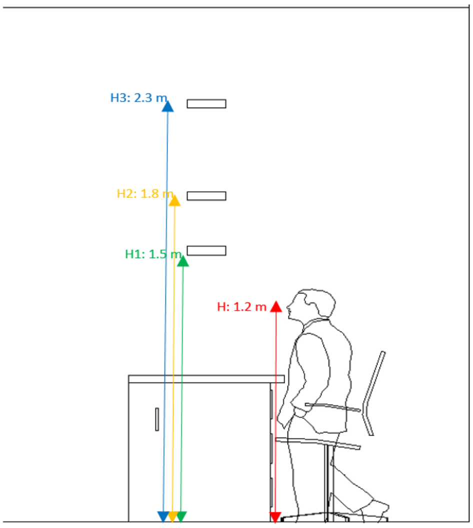
A simulation methodology was implemented for both L1 and L2 luminaires with a CCT of 3800K to meet the illuminance level requirements of the office workers on both the vertical and horizontal planes. The EV and dynamic luminaire mounting height were evaluated accordingly. The simulation was conducted using DIALux Evo [70] and Microsoft Excel for the open plan office.

The illuminance levels were calculated using a horizontal calculation surface with desk dimensions of 0.8×1.3 meters, set at a height of 0.8 meters above the finished floor level. Additionally, calculations to EV were proposed at a height of 1.2 meters above the finished floor, aligned with the human eye level and direction of view. Figure 4.10, shows the details of suggested arrangement for the open office. Figure 4.11. (A) shows simulated open-plan office and (B) shows occupants' view direction height at H: 1.2 m and L1 and L2 mounting heights at H1, H2, H3. The occupants' view direction at three main lighting heights, while the Figure 4.11 B presents a schematic of an occupant. The EH at the desk and EV at the occupant's eye level were evaluated at three different heights: H1 at 1.5 meters, H2 at 1.8 meters, and H3 at 2.3 meters above the finished floor, with a 1.2 meter distance from the wall behind the occupant.

Figure 4.10: Suggested arrangement for the open office



(A)



(B)

Figure 4.11: (A): simulated open-plan office. (B): participant's view direction height at H: 1.2 m and L1 and L2 mounting heights at H1, H2, H3.

We evaluated the desired EV and dynamic luminaire mounting height to determine the Optimum Luminaire Height (OLH) is the H2 which is 1.8m above finished floor. To obtain the CS, 0.3 and EML above 275 on the H2 dimming rate of 40% applied on luminaires, in order to gain not only minimum target amounts but also energy saving with the OLH. Derived from the simulation outcomes, two threshold heights, CS: 0.3 and 0.4 for OLH, were established for the lighting luminaires. The simulation results demonstrate that at OLH, CS exceeds 0.4, which surpasses the target of our approach [63]. Hence, 40% dimming is implemented in the H2 scenario to maintain CS at 0.3, same as the H1 and H3 scenarios as shown on Table 4.3.

Table 4.3: Left: Simulation results of L1. Right: Simulation results of L2.

L1			
Height (m)	1.5	1.8	2.3
EV 1.2m (lux)	532	872	561
EV dimmed (lux)	-	525	-
CS	0.3	0.4	0.3
CS dimmed	-	0.3	-
EML (m-lux)	346	568	365
EML dimmed (m-lux)	-	341	-
MR	0.651	0.651	0.651
EH Desk (lux)	1505	1011	580
EH Desk dimmed (lux)	-	607	-

L2			
Height (m)	1.5	1.8	2.3
EV 1.2m (lux)	437	678	432
EV dimmed (lux)	-	387	-
CS	0.3	0.4	0.3
CS dimmed	-	0.3	-
EML (m-lux)	316	490	312
EML dimmed (m-lux)	-	279	-
MR	0.722	0.722	0.722
EH Desk (lux)	1100	763	460
EH Desk dimmed (lux)	-	445	-

In Phase 2 of the study, the same open-plan office arrangement simulation was revisited, this time exploring the concept of variable CCTs at two specific setups: L1 with H3 at 2.3m and L2 with H2 at 1.8m.Under the L1 setup, the CCT chosen was 3800K, while under L2, a range of CCTs including 2700K, 3800K, and 6000K were investigated. These CCTs were accordingly adjusted to operate at varying rates: 75%, 60%, and 40% of the total luminaire luminous flux output.

Furthermore, the study ensured that both a CS value of 0.3 and the minimum target EML were achieved. For the CCTs investigated, the corresponding EML values were found to be 284 for 3800K, 284 for 2700K, and 283 for 6000K, respectively. By exploring the impact of these variable CCTs on the lighting quality and comfort of office workers, Phase 2 aimed to refine the understanding of optimal lighting solutions for open-plan office environments, thus contributing to the ongoing discourse on human-centered lighting design.

4.1.2. Experimental study

Using the CS calculator requires the insertion of SPD values of luminaires, highlighting the importance of accurate data. Similarly, to assess the EML, the same SPD values are input into the EML calculator file to determine the EML amount for each individual luminaire. The SPDs of the sample luminaires were measured experimentally at the Laboratory of the Energy Institute of Istanbul Technical University, as illustrated in Figure 4.12. The SPD values are listed within the wavelength range of 380-730 nm for each individual luminaire which is measured with Labsphere integrating sphere spectroradiometer [71] and listed in Appendix A, Table A.3.

Figure 4.12: Measuring SPD of Sample luminaire.

The measured reflectance values for the office are measured as follows: 40% for the floor, 90% for the walls, 90% for the ceiling, 2.5% for chairs, and 86% for desks and drawers with laboratory and high precision luminance meter series LMT L1009 [72].

Based on the simulation results, two threshold heights at 1.5m and 2.3m above finished floor, values for CS:0.3 and one OLH at 1.8m above finished floor, were defined for the lighting luminaires, which is the best scenario to dim luminaire and save energy due to access CS:0.3 because in this case CS equals to 0.4 which is over target for our proposal. These scenarios, derived from the simulation results, were meticulously implemented in the sample office environment. Recognizing the necessity for an adaptable mechanism to control luminaire height, extensive efforts were made to develop a dynamic device capable of seamlessly managing various lighting scenarios. Consequently, we devised and integrated the innovative apparatus, showcased in Figure 4.13, to facilitate precise adjustments to luminaire height in accordance with anticipated conditions. This solution not only enhances flexibility but also ensures optimal lighting conditions tailored to specific requirements, thereby augmenting overall efficiency and comfort within the workspace.

Figure 4.13: Adjustable suspended luminaire mechanism.

During office hours, participants completed surveys and tests to gather subjective feedback on various aspects, including comfort criteria, workplace satisfaction, lighting quality, environmental satisfaction, alertness, mood, and motivation. Figure 4.11 illustrates the layout of the study office, which intentionally lacks access to daylight, and Table 4.4 provides information about the open-plan office. It is important to note that all windows in the office were covered to eliminate the influence of natural daylight, creating a controlled environment solely influenced by the experimental artificial lighting conditions. And Figure 4.14 presents frames of study open plan office.

Table 4.4: The results of the measurements of the office.

L1			
Height (m)	1.5	1.8	2.3
EV 1.2m (lux)	523	853	550
EV dimmed (lux)	-	520	-
CS	0.3	0.4	0.31
CS dimmed	-	0.3	-
EML (m-lux)	340	555	358
EML dimmed (m-lux)	-	338	-
MR	0.651	0.651	0.651
EH Desk (lux)	2026	1200	752
EH Desk dimmed (lux)	-	870	-

L2			
Height (m)	1.5	1.8	2.3
EV 1.2m (lux)	420	630	400
EV dimmed (lux)	-	393	-
CS	0.3	0.4	0.3
CS dimmed	-	0.3	-
EML (m-lux)	303	455	289
EML dimmed (m-lux)	-	284	-
MR	0.722	0.722	0.722
EH Desk (lux)	1137	760	521
EH Desk dimmed (lux)	-	520	-

Figure 4.14: Frames of study open plan office

Phase 2 of the study focuses on the same open plan office layout, but with a new approach involving variable CCTs for L2H2 and fixed CCT for L1H3. In this phase, L1 is examined with a fixed CCT of 3800K at an operation rate of 100% due to the height selection of H3 (2.3m above finished floor), while L2 is investigated with variable CCTs of 2700K, 3800K, and 6000K, each set at operation rates of 75%, 60%, and 40% of the total luminaire output, respectively. Notably, these configurations ensure that the minimum CS requirement of 0.3 is met. In terms of EML values, EML of L1 was set at 358, while L2 at different CCTs yields varying results: EML: 275.5 for 2700K, EML: 293 for 3800K, and EML: 319 for 6000K. This phase aims to explore the impact of variable CCTs on visual comfort and circadian response within the office environment.

4.2. Surveys

The research was conducted between March 2023 and September 2023, involving Eighty-four participants with an average experimental period of 100 minutes. The study's primary objective was to conduct a comparative analysis of two luminaires featuring dynamic height adjustments, specifically tailored for human-centered lighting applications in office settings. To achieve this goal, subjective feedback was systematically collected from participants through a series of surveys and tests administered within predefined timeframes. These assessments covered a wide range of aspects, including comfort criteria, workplace satisfaction, perceived lighting quality, overall environmental satisfaction, levels of alertness, mood states, and motivational factors. Notably, the research was conducted within the context of an open-plan office environment situated at Istanbul Technical University.

The Figure 4.15 illustrates the spatial arrangement of participants at their individual desks within the office space. Each participant underwent a series of surveys tailored to evaluate different lighting scenarios, allowing for a comprehensive examination of their experiences and preferences. It's worth mentioning that the study comprised two distinct phases, even within the survey components, enabling a thorough investigation into the impact of dynamic lighting solutions on various aspects of office performance and satisfication.

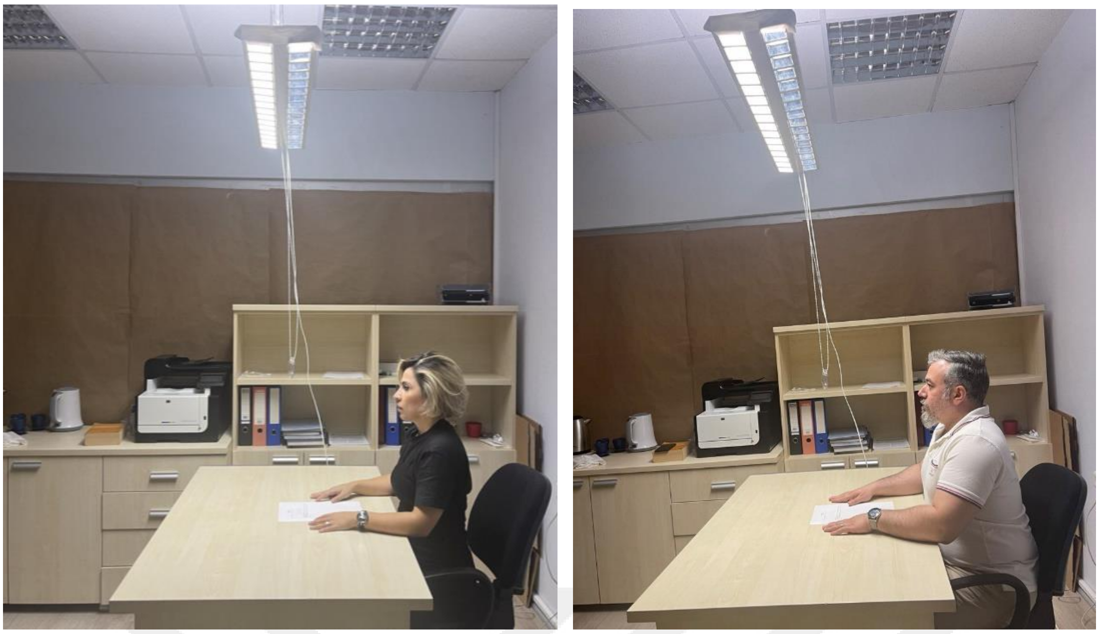


Figure 4.15: Frames showing participants' positions in the study open-plan office.

The primary objective of the study was to investigate how different lighting conditions influenced individuals' experiences. Alertness was found to be significant in four out of five studies that utilized the Karolinska Sleepiness Scale (KSS) [73]. So, trials were conducted within the office space, with each experiment consisting of three distinct sessions. In Session 1, participants give their feedbacks on KSS1 test, demographic information and Positive and Negative Affect Schedule (PANAS) [74] answers. Session 2 focused on evaluating participants' visual perception using Questionnaire 1 (Q1), a cognitive performance test, and Questionnaire 2 (Q2), a proofreading task, under the lighting arrangement at H1, H2, and H3 conditions. Session 3 aimed to gather valuable participant feedback regarding their experiences with the specific lighting systems used in the experiments and KSS2 feedbacks.

To ensure a representative sample, the participants were carefully balanced, with male and female participants, divided into three age groups: 20-30, 30-40, and above 40. The study employed a unique approach due to the office layout and limited desk availability. The comprehensive study aimed to thoroughly investigate the impact of lighting conditions on occupants' cognitive performance, visual perception, and subjective experiences within an office setting. The deliberate variations in luminaire heights and the consideration of participant demographics contribute to the robustness of the study's findings. At the beginning of the study, KSS1 and demographic information about the participants was collected, including age, gender, eye disorders, and whether they wore eyeglasses or contacts while working.

It is worth noting that the participants' workstations were located in an open office area with suspended lighting. The objective of the study was to develop a research methodology that improves the current understanding of how lighting affects the physiological and psychological responses of individuals in an office environment. To ensure clarity for the participants and facilitate statistical analysis, most of the questions were presented in a 5-point Likert scale format. Figure 4.16 illustrates the experimental procedure that was followed for each participant.

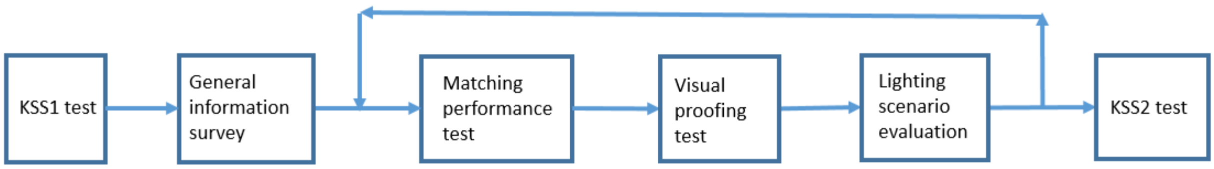


Figure 4.16: Experimental procedure that followed for each participant.

5. RESULTS

This section offers an in-depth exploration of the outcomes obtained from both Phase 1 and Phase 2 of the study. Phase 1 of the study acts as a critical foundation for revealing the key observations derived from the application of human-centered lighting solutions designed specifically for open-plan office environments. Through analysis, phase 1 seeks a way on the efficacy of these solutions in addressing the multifaceted needs of office occupants, ranging from visual comfort to overall performance.

In contrast, Phase 2 represents a crucial step forward in the research journey, functioning as a validation study aimed at corroborating the findings observed in Phase 1. By delving deeper into the impact of CCTs on the productivity and satisfaction of office workers, Phase 2 aims to provide further clarity and validation to the initial hypotheses posited in Phase 1. Together, these complementary phases offer a comprehensive understanding of the intricate interplay between lighting design and human factors within the human centered office environment lighting.

5.1 Results of Phase 1 of Study

Questionnaires based on opinions were developed to evaluate the comfort criteria of the occupants. The research study of Phase 1 was conducted between March 2023 and July 2023, involving 60 participants with an average experimental period of 100 minutes. Figure 5.1. presents demographic information about the participants.

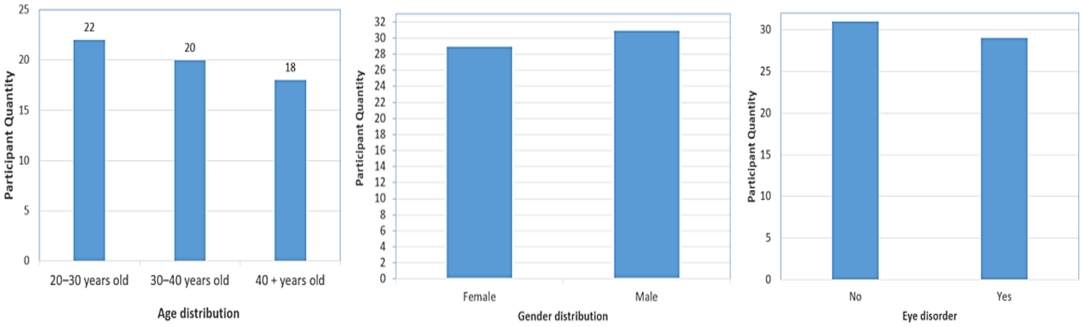


Figure 5.1: Demographic information about the participants.

The participants' levels of sleepiness were measured using the KSS, which was administered both at the beginning and end of the survey. At the beginning of each set of luminaires, participants were asked about their satisfaction with their workplace, specifically at their workstations. Subjective feedback regarding the comfort of office furnishings and the adequacy of the available space for individual work was also collected as Figure 5.2.

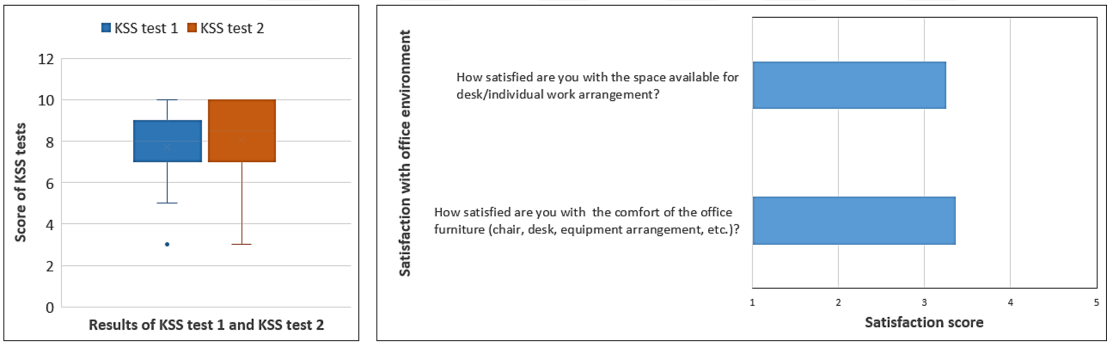


Figure 5.2: Left: KSS 1 and KSS 2 answers; Right: satisfaction with office environment.

Furthermore, the effect on participants was assessed using the short form of the panas. The 10 items of the PANAS short form were presented in a random order and average of the 5-point Likert scale is presented at feedback scores of PANAS survey. Additionally, three questions were included to measure participants' current mood, physical well-being, and motivation to complete their ongoing tasks. The PANAS survey was provided at the beginning of the tests, and the results are shown in Figure 5.3.

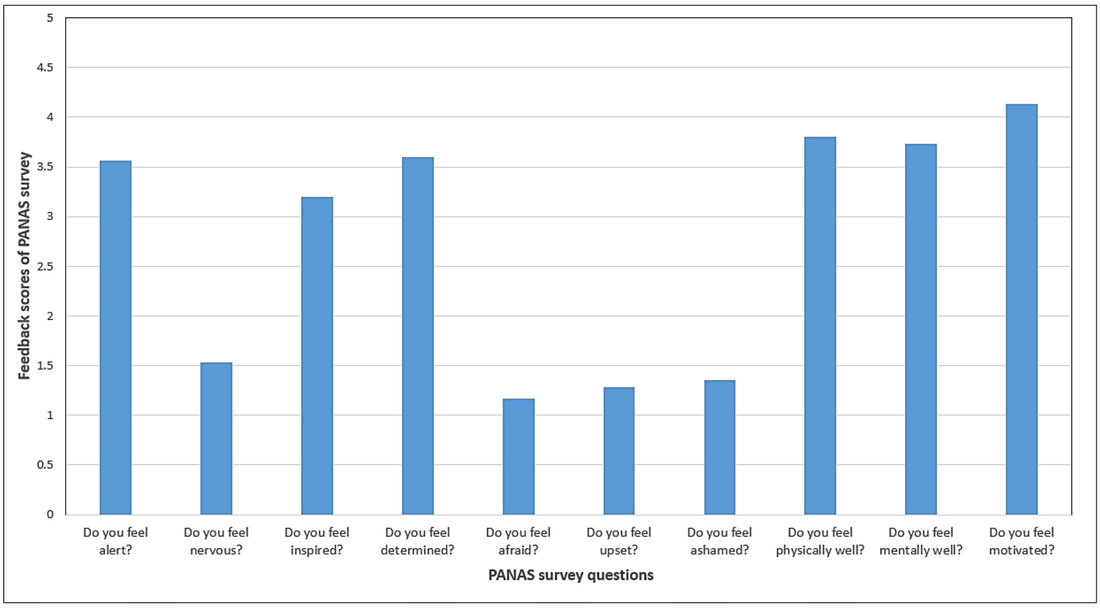


Figure 5.3: PANAS survey questions and feedback from 60 participants.

The lighting satisfaction survey was conducted at the conclusion of each set of luminaires. Participants were asked to indicate their level of satisfaction by responding to the following statements: "I am satisfied with the lighting", "There is an appropriate level of illumination for the task I am currently performing" and "The color of the light is pleasant" and "The lighting is unified on the desk" and "The height of lighting is pleasant”. Additionally, they were requested to rate the lighting on a scale ranging from Uncomfortable to Comfortable, Not Uniform to Uniform, and Unsuitable to Suitable, taking into consideration the luminaire height. Figure 5.4 presents the comparative satisfaction results among H1, H2, and H3 for L1 and L2.

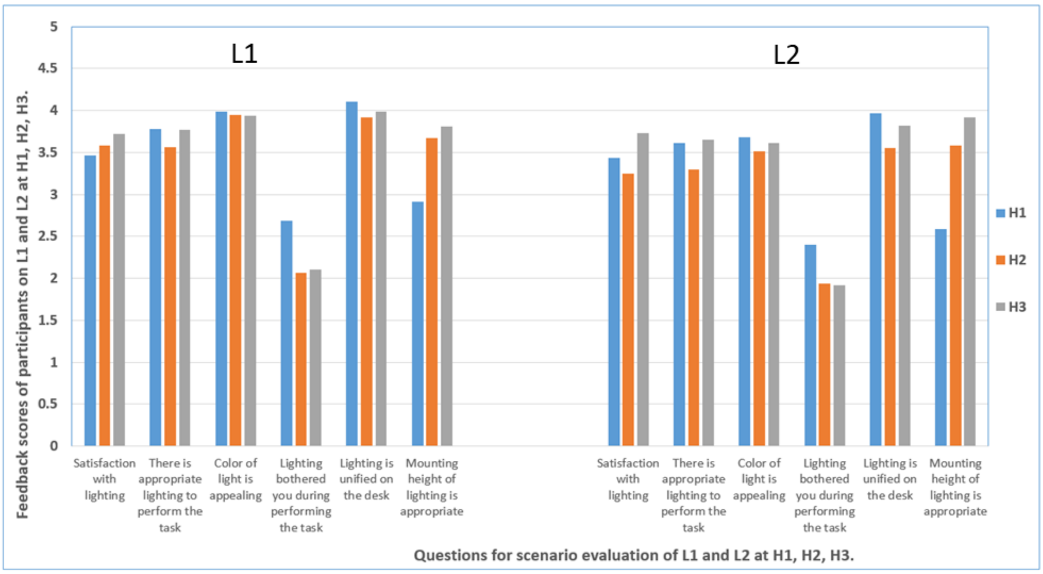


Figure 5.4: The pleasure rating reviews of participants at H1, H2, H3.

The EML and CS values were calculated for each desk based on the calculated and measured eye-level illuminances and SPDs. All the collected data were used to compare the evaluation differences between L1 and L2 and preferences among H1, H2, and H3 scenarios. Participants' performance was assessed not only on Q1 and Q2 but also on their preferences for lighting height and comfortability. This provided an approximate recommendation for the OLH and spectrum quality for non-visual analysis. Statistical methods were applied to obtain significant outcomes from the data.

5.1.1. Statistical results of KSS

A p value of 0.05 indicates that there is only a 5% chance that the observed results in the sample occurred by chance [75]. P values of the study is listed in bolded text at the tables. The hypothesis that light affects the rate of sleepiness in occupants, which was tested using the KSS tests, resulted in a Pearson correlation p value of 0.001 for KSS test 1 and KSS test 2. The dataset includes responses from 60 occupants, with KSS survey data collected at both the beginning and end of the survey period.

5.1.2. Statistical results of participants' performance on H1, H2, H3 regarding age, gender, and eye disorder factor

The statistical significance of the observed effects on lighting satisfaction, environmental satisfaction, age, gender, and eye disorders was analyzed using Multivariate Analysis Of Variance (MANOVA) tests through Minitab software. The experiment aimed to explore human-centered lighting conditions alongside physiological comfort conditions, using Q1 and Q2 to gather data on error quantities (E) and time periods (t) as measurement scales, alongside participants' preferences based on their comfort criteria. The results regarding Q1 and Q2, which include illuminance levels on the desk correlating with performance, are presented in terms of error quantities which are the incorrect answers to the tests and the time duration that participants spent during the answering Q1 and Q2 at each scenarios listed in Table 5.1, indicate that lighting environmental satisfaction has a significant effect on the age factor of the participants. Within each of the H1, H2, and H3 conditions, the performance of occupants at each illumination level demonstrates a partial dependence on the age group.

Table 5.1: Results of MANOVA on illuminance level on the desk with matching performance and proofing test.

MANOVA				P Value		
Height of luminaire	Description	Tests	Preference	Factors	L1	L2
H1	illuminance level on the desk/matching performance	Q1	Errors	Gender	0.36	0.22
				eye disorder	0.76	0.56
				age	0.95	0.54
H1	illuminance level on the desk/matching performance	Q1	Time	Gender	0.95	0.32
				eye disorder	0.69	0.28
				age	0.04	0.17
H1	illuminance level on the desk/proofing test	Q2	Errors	Gender	0.50	0.58
				eye disorder	0.58	0.19
				age	0.03	0.27
H1	illuminance level on the desk/proofing test	Q2	Time	Gender	0.98	0.45
				eye disorder	0.25	0.45
				age	0.10	0.10
H2	illuminance level on the desk/matching performance	Q1	Errors	Gender	0.78	0.90
				eye disorder	0.01	0.80
				age	0.19	0.44
H2	illuminance level on the desk/matching performance	Q1	Time	Gender	0.10	0.06
				eye disorder	0.20	0.94
				age	0.08	0.02
H2	illuminance level on the desk/proofing test	Q2	Errors	Gender	0.69	0.08
				eye disorder	0.77	0.72
				age	0.10	0.04
H2	illuminance level on the desk/proofing test	Q2	Time	Gender	0.41	0.45
				eye disorder	0.25	0.44
				age	0.01	0.16
H3	illuminance level on the desk/matching performance	Q1	Errors	Gender	0.74	0.34
				eye disorder	0.10	0.43
				age	0.31	0.26
H3	illuminance level on the desk/matching performance	Q1	Time	Gender	0.44	0.49
				eye disorder	0.11	0.27
				age	0.16	0.14
H3	illuminance level on the desk/proofing test	Q2	Errors	Gender	0.81	0.34
				eye disorder	0.42	0.43
				age	0.94	0.26
H3	illuminance level on the desk/proofing test	Q2	Time	Gender	0.63	0.38
				eye disorder	0.08	0.54
				age	0.02	0.10

5.1.3: Statistical results of participants' performance levels between H1, H2, H3

An analysis was conducted on Q1 and Q2 to examine the number of errors and the time taken to complete the tasks. This analysis utilized a t-test to provide meaningful insights into the performance levels of occupants at different luminaire heights H1, H2, and H3. The differences in light distributions curve also became evident, with p values below 0.05 indicating statistical significance. The correlations between the three heights were investigated using the t-test, as illustrated in Table 5.2 in description part Q1, Q2 refers to questionnaires, E and t refers to error quantity and time that spent on Q1 and Q2 and LH refers luminaire and height of mounting. The highest correlations were observed between luminaire height and the time taken to complete the tasks.

Table 5.2: Results of T-Test on Performance level of occupants between H1, H2, and H3

T-Test	P Value	
Description	L1	L2
Q1 E LH1, Q1 E LH2	0.704	0.028
Q1 E LH1, Q1 E LH3	0.358	0.35
Q1 E LH2, Q1 E LH3	0.497	0.132
Q1 t LH1, Q1 t LH2	0.208	0.153
Q1 t LH1, Q1 t LH3	0.024	0.038
Q1 t LH2, Q1 t LH3	0.191	0.5
Q2 E LH1, Q2 E LH2	0.305	0.252
Q2 E LH1, Q2 E LH3	0.274	0.008
Q2 E LH2, Q2 E LH3	0.054	0.036
Q2 t LH1, Q2 t LH2	0.346	0.095
Q2 t LH1, Q2 t LH3	0.012	0.07
Q2 t LH2, Q2 t LH3	0.011	0.511

5.1.4. Statistical results of participants' performance between L1 and L2

In the paired t-test, the p values of 0.000 and 0.008 indicate that the data were collected from tests involving the light distribution curve of the luminaires. The t-test was applied to assess the difference between L1 and L2 lighting conditions. The results supported a distinction in the performance of occupants between L1H1 vs. L2H1 and L1H2 vs. L2H2. However, the findings indicated that the lighting conditions of L1H3 and L2H3 were not significantly different. As shown in Table 5.3, E refers the errors quantity and t refers the consumed time to answer the Q1 and Q2 with confidence interval (CI) rate of 95%.

Table 5.3: T-Test applied to test the difference between L1 and L2 lighting performances

Method	Description	P Value
T-Test	Paired T-Test and CI: Q1 E L1H1, Q1 E L2H1	0.546
	Paired T-Test and CI: Q1 t L1H1 (sec), Q1 t L2H1 (sec)	0
	Paired T-Test and CI: Q2 E L1H1, Q2 E L2H1	0.063
	Paired T-Test and CI: Q2 t L1H1 (sec), Q2 t L2H1 (sec)	0.288
	Paired T-Test and CI: Q1 E L1H2, Q1 E L2H2	0.117
	Paired T-Test and CI: Q1 t L1H2 (sec), Q1 t L2H2 (sec)	0.095
	Paired T-Test and CI: Q2 E L1H2, Q2 E L2H2	0.143
	Paired T-Test and CI: Q2 t L1H2 (sec), Q2 t L2H2 (sec)	0.008
	Paired T-Test and CI: Q1 E L1H3, Q1 E L2H3	0.568
	Paired T-Test and CI: Q1 t L1H3 (sec), Q1 t L2H3 (sec)	0.95
	Paired T-Test and CI: Q2 E L1H3, Q2 E L2H3	0.052
	Paired T-Test and CI: Q2 t L1H3 (sec), Q2 t L2H3 (sec)	0.35

5.1.5. Statistical results of participants' performance dependent on gender

As the data on participants' gender was not normally distributed, the Mann-Whitney test was employed to evaluate the difference in performance among occupants under different lighting scenarios. The analysis results are presented in Table 5.4. Females demonstrated shorter performance times on Q1 L1H1 compared to males, with a sample size of 29 for females and 31 for males [76].

Table 5.4: Mann-Whitney Test applied lighting performances of participants depend on the gender.

Method	Description	P Value
Mann-Whitney Test	Mann-Whitney Test and CI: Q1 E L1H1 Female, Q1 E L1H1 Male	0.5675
	Mann-Whitney Test and CI: Q1 t L1H1 (sec) Female, Q1 t L1H1 (sec) Male	0.8302
	Mann-Whitney Test and CI: Q2 E L1H1 Female, Q2 E L1H1 Male	0.7106
	Mann-Whitney Test and CI: Q2 t L1H1 (sec) Female, Q2 t L1H1 (sec) Male	0.7448
	Mann-Whitney Test and CI: Q1 E L1H2 Female, Q1 E L1H2 Male	0.8116
	Mann-Whitney Test and CI: Q1 t L1H2 (sec) Female, Q1 t L1H2 (sec) Male	0.0357

Table 5.4 (continued): Mann-Whitney Test applied lighting performances of participants depend on the gender.

Method	Description	P Value
Mann-Whitney Test	Mann-Whitney Test and CI: Q2 E L1H2 Female, Q2 E L1H2 Male	0.6736
	Mann-Whitney Test and CI: Q2 t L1H2 (sec) Female, Q2 t L1H2 (sec) Male	0.5944
	Mann-Whitney Test and CI: Q1 E L1H3 Female, Q1 E L1H3 Male	0.7108
	Mann-Whitney Test and CI: Q1 t L1H3 (sec) Female, Q1 t L1H3 (sec) Male	0.2059
	Mann-Whitney Test and CI: Q2 E L1H3 Female, Q2 E L1H3 Male	0.8463
	Mann-Whitney Test and CI: Q2 t L1H3 (sec) Female, Q2 t L1H3 (sec) Male	0.7005
	Mann-Whitney Test and CI: Q1 E L2H1 Female, Q1 E L2H1 Male	0.2978
	Mann-Whitney Test and CI: Q1 t L2H1 (sec) Female, Q1 t L2H1 (sec) Male	0.3004
	Mann-Whitney Test and CI: Q2 E L2H1 Female, Q2 E L2H1 Male	0.9109
	Mann-Whitney Test and CI: Q2 t L2H1 (sec) Female, Q2 t L2H1 (sec) Male	0.7005
	Mann-Whitney Test and CI: Q1 E L2H2 Female, Q1 E L2H2 Male	0.6322
	Mann-Whitney Test and CI: Q1 t L2H2 (sec) Female, Q1 t L2H2 (sec) Male	0.1169
	Mann-Whitney Test and CI: Q2 E L2H2 Female, Q2 E L2H2 Male	0.2710
	Mann-Whitney Test and CI: Q2 t L2H2 (sec) Female, Q2 t L2H2 (sec) Male	0.9646
	Mann-Whitney Test and CI: Q1 E L2H3 Female, Q1 E L2H3 Male	0.1035
	Mann-Whitney Test and CI: Q1 t L2H3 (sec) Female, Q1 t L2H3 (sec) Male	0.2936
	Mann-Whitney Test and CI: Q2 E L2H3 Female, Q2 E L2H3 Male	0.2370
	Mann-Whitney Test and CI: Q2 t L2H3 (sec) Female, Q2 t L2H3 (sec) Male	0.7337

5.1.6: Statistical results of participants' performance regarding age groups

As the data on participants' age groups were not normally distributed, the Mann-Whitney test was utilized to evaluate the difference in performance among occupants under lighting scenarios. The analysis results are presented in Table 5.5. Performance is categorized based on the age groups of the participants, with a sample size of 22 for those aged 20-30 years, 20 for those aged 30-40 years, and 18 for those aged 40 years and older.

Table 5.5: Mann-Whitney Test applied lighting performances of participants depend on the age groups.

Method	Description	P Value
Mann-Whitney Test	Q1 E L1H1 20-30, Q1 E L1H1 30-40	0.8848
	Q1 t L1H1 (sec)20-30, Q1 t L1H1 (sec)30-40	0.0098
	Q2 E L1H1 20-30, Q2 E L1H1 30-40	0.0117
	Q2 t L1H1 (sec)20-30, Q2 t L1H1 (sec)30-40	0.1548
	Q1 E L1H2 20-30, Q1 E L1H2 30-40	0.3872
	Q1 t L1H2 (sec)20-30, Q1 t L1H2 (sec)30-40	0.6963
	Q2 E L1H2 20-30, Q2 E L1H2 30-40	0.3993
	Q2 t L1H2 (sec)20-30, Q2 t L1H2 (sec)30-40	0.0453
	Q1 E L1H3 20-30, Q1 E L1H3 30-40	0.2652
	Q1 t L1H3 (sec)20-30, Q1 t L1H3 (sec)30-40	0.0990
	Q2 E L1H3 20-30, Q2 E L1H3 30-40	0.7748
	Q2 t L1H3 (sec)20-30, Q2 t L1H3 (sec)30-40	0.0333
	Q1 E L2H1 20-30, Q1 E L2H1 30-40	0.2235
	Q1 t L2H1 (sec)20-30, Q1 t L2H1 (sec)30-40	0.0068
	Q2 E L2H1 20-30, Q2 E L2H1 30-40	0.3530
	Q2 t L2H1 (sec)20-30, Q2 t L2H1 (sec)30-40	0.0642
	Q1 E L2H2 20-30, Q1 E L2H2 30-40	0.6219
	Q1 t L2H2 (sec)20-30, Q1 t L2H2 (sec)30-40	0.0572
	Q2 E L2H2 20-30, Q2 E L2H2 30-40	0.9884
	Q2 t L2H2 (sec)20-30, Q2 t L2H2 (sec)30-40	0.3198
	Q1 t L2H3 (sec)20-30, Q1 t L2H3 (sec)30-40	0.0333
	Q2 E L2H3 20-30, Q2 E L2H3 30-40	0.4599
	Q2 t L2H3 (sec)20-30, Q2 t L2H3 (sec)30-40	0.1946
	Q1 E L1H1 20-30, Q1 E L1H1 40+	0.7760
	Q1 t L1H1 (sec)20-30, Q1 t L1H1 (sec) 40+	0.0685
	Q2 E L1H120-30, Q2 E L1H1 40+	0.0489
	Q2 t L1H1 (sec)20-30, Q2 t L1H1 (sec) 40+	0.0553
	Q1 E L1H220-30, Q1 E L1H2 40+	0.3888
	Q1 t L1H2 (sec)20-30, Q1 t L1H2 (sec) 40+	0.0375
	Q2 E L1H220-30, Q2 E L1H2 40+	0.4040
	Q2 t L1H2 (sec)20-30, Q2 t L1H2 (sec) 40+	0.0119
	Q1 E L1H320-30, Q1 E L1H3 40+	0.9140
	Q1 t L1H3 (sec)20-30, Q1 t L1H3 (sec) 40+	0.0375
	Q2 E L1H320-30, Q2 E L1H3 40+	0.9749
	Q2 t L1H3 (sec)20-30, Q2 t L1H3 (sec) 40+	0.0129
	Q1 E L2H120-30, Q1 E L2H1 40+	0.4659
	Q1 t L2H1 (sec)20-30, Q1 t L2H1 (sec) 40+	0.2264
	Q2 E L2H120-30, Q2 E L2H1 40+	0.1557
	Q2 t L2H1 (sec)20-30, Q2 t L2H1 (sec) 40+	0.0216
	Q1 t L2H2 (sec)20-30, Q1 t L2H2 (sec) 40+	0.0110
	Q2 E L2H2 20-30, Q2 E L2H2 40+	0.4141

Table 5.5 (continued): Mann-Whitney Test applied lighting performances of participants depend on the age groups.

Method	Description	P Value
Mann-Whitney Test	Q2 t L2H2 (sec)20-30, Q2 t L2H2 (sec) 40+	0.0945
	Q1 t L2H3 (sec)20-30, Q1 t L2H3 (sec) 40+	0.0328
	Q2 E L2H320-30, Q2 E L2H3 40+	0.1210
	Q2 t L2H3 (sec)20-30, Q2 t L2H3 (sec) 40+	0.0286
	Q1 E L1H1 30-40, Q1 E L1H1 40+	0.9083
	Q1 t L1H1 (sec)30-40, Q1 t L1H1 (sec) 40+	0.4472
	Q2 E L1H130-40, Q2 E L1H1 40+	0.6114
	Q2 t L1H1 (sec)30-40, Q2 t L1H1 (sec) 40+	0.5786
	Q1 t L1H2 (sec)30-40, Q1 t L1H2 (sec) 40+	0.1438
	Q2 E L1H230-40, Q2 E L1H2 40+	0.9372
	Q2 t L1H2 (sec)30-40, Q2 t L1H2 (sec) 40+	0.4299
	Q1 E L1H330-40, Q1 E L1H3 40+	0.3643
	Q1 t L1H3 (sec)30-40, Q1 t L1H3 (sec) 40+	1
	Q2 E L1H3 30-40, Q2 E L1H3 40+	0.7666
	Q2 t L1H3 (sec)30-40, Q2 t L1H3 (sec) 40+	0.6610
	Q1 E L2H130-40, Q1 E L2H1 40+	0.6182
	Q1 t L2H1 (sec)30-40, Q1 t L2H1 (sec) 40+	0.2794
	Q2 E L2H130-40, Q2 E L2H1 40+	0.6397
	Q2 t L2H1 (sec)30-40, Q2 t L2H1 (sec) 40+	0.9534
	Q1 t L2H2 (sec)30-40, Q1 t L2H2 (sec) 40+	0.4648
	Q2 E L2H230-40, Q2 E L2H2 40+	0.4608
	Q2 t L2H2 (sec)30-40, Q2 t L2H2 (sec) 40+	0.5392
	Q1 E L2H3 30-40, Q1 E L2H3 40+	0.3448
	Q1 t L2H3 (sec)30-40, Q1 t L2H3 (sec) 40+	0.9767
	Q2 E L2H3 30-40, Q2 E L2H3 40+	0.4429
	Q2 t L2H3 (sec)30-40, Q2 t L2H3 (sec) 40+	0.5587

5.1.7. Statistical results of the observed prevalence of H1, H2, H3 and L1, L2

In terms of the performance level of the 60 participants, the best performance was observed at L1H3 and L2H2, as shown in Table 5.6 participants achieved their highest performance at H3 for L1 and H2 for L2 among H1, H2, H3. Hence, the best case is L1H3 due to the test results and participants preference on scenarios.

Table 5.6: Comparison of participants' performance for L1 and L2 under each H1, H2, H3 condition.

Luminaire/Height	ERROR		TIME	
	Matching Performance	Visual Proof	Matching Performance	Visual Proof
L1H1	✓	✓✓	✓	✓✓
L1H2	✓✓	✓	✓✓	✓
L1H3	✓✓✓	✓✓✓	✓✓✓	✓✓✓
L2H1	✓	✓✓✓	✓✓✓	✓

Table 5.6 (continued): Comparison of participants' performance for L1 and L2 under each H1, H2, H3 condition.

L2H2	✓✓	✓✓	✓✓✓	✓✓
L2H3	✓✓	✓	✓	✓✓✓

✓: The worse performance results; ✓✓: moderate performance results; ✓✓✓: the best performance results.

The comfort criteria of the participants are also important in this study. Although H3 is the most preferred luminaire height among H1, H2, and H3 at L1 at Table 5.7, but the performance of the participants is more successful at L2H2 of L2 as shown in Table 5.6. Accordingly, at scenario L2H2 performance results are successful but due to preference feedbacks of the participants, scenario L2H3 is successful.

Table 5.7: Comparison of the prevalence of participants between L1 and L2 under each H1, H2, H3 condition.

Luminaire /Height	Satisfaction with Lighting	There Is Appropriate Lighting to Perform the Task	Color of Light Is Appealing	Lighting Bothered You during Task	Lighting is Unified on the Desk	Mounting Height of Lighting Is Appropriate
L1H1	✓	✓✓✓	✓✓✓	✓	✓✓✓	✓
L1H2	✓✓	✓	✓✓	✓✓✓	✓	✓✓
L1H3	✓✓✓	✓✓	✓	✓✓	✓✓	✓✓✓
L2H1	✓✓	✓✓	✓✓✓	✓	✓✓✓	✓
L2H2	✓	✓	✓	✓✓	✓	✓✓
L2H3	✓✓✓	✓✓✓	✓✓	✓✓✓	✓✓	✓✓✓

✓: The worse performance results; ✓✓: moderate performance results; ✓✓✓: the best performance results.

5.1.8: Results of participants' preference between L2H2 and L1H3

Regarding the section, the evaluation of the most successful scenarios, L1H3 and L2H2, aimed to observe the differences in lighting scenarios between the two. The most favorable scenario is observed in L1H3 not only in performance but also in the preferences expressed by the participants. Conversely, the results of L2H2 indicate that while participants' performance is successful, their preference is lower compared to L2H3. Analysis of variance (ANOVA) was applied to the data, and the results are presented in Table 5.8. The analysis indicates a statistically significant difference in the satisfaction level of lighting, suitable illuminance level on the desk, uniformity of lighting, pleasantness of light color, unpleasantness of lighting during tests, and the height of lighting between L1 and L2.

Table 5.8: Prevalence rate of participants' preference between L1H3 and L2H2.

Method	Description	P Value
ANOVA	Satisfaction of lighting versus L1H3-L2H2 system	0.014
	There is appropriet lighting for the task versus L1H3-L2H2 system	0.016
	Color of light is appealing versus L1H3-L2H2 system	0.085
	Lighting bothered you during task versus L1H3-L2H2 system	0.425
	Lighting is unified on desk versus L1H3-L2H2 system	0.011
	Mounting height of lighting is suitable versus L1H3-L2H2 system	0.79

5.2. Results of Phase 2 of Study

Phase 2 of the research study was conducted between September 2023 and November 2023, involving 24 participants, each engaging in the study for an average period of 80 minutes. The primary objective was to compare the effectiveness of two selected office lighting heights, gathering feedback through surveys and tests conducted under different CCTs.

Participants provided feedback on various aspects, including comfort criteria, workplace satisfaction, lighting quality, environmental satisfaction, alertness, mood, and motivation. This research was carried out in the same open-plan office space located at Istanbul Technical University, consistent with Phase 1 of the study.

To ensure a representative sample, the participants were meticulously balanced, with 13 male and 11 female participants, distributed across three age groups: 20-30, 30-40, and above 40, each group comprising 8 participants.

At the commencement of the study, demographic information about the participants was collected. Notably, 17 participants reported having eye disorders and utilized eyeglasses or contacts while performing tasks. Figure 5.5 provides a detailed overview of the demographic composition of the participants in Phase 2.

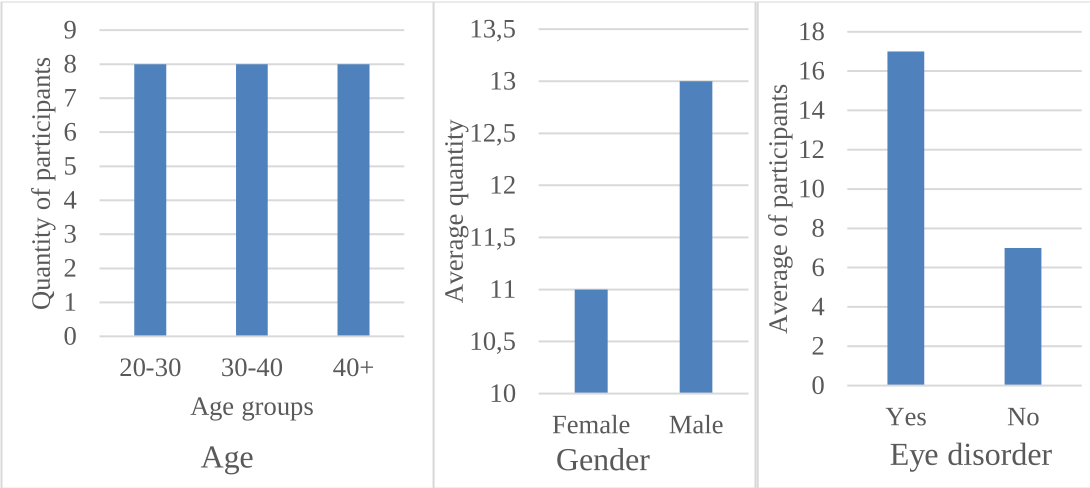


Figure 5.5: Demographic information about the participants at phase 2.

The primary objective of the study was to investigate how different CCTs influenced individuals' experiences. Four scenarios were conducted within the office space, with each experiment consisting of three distinct sessions. In Session 1, participants performed cognitive tasks to assess their performance under each scenario. Session 2 focused on evaluating participants' visual perception using Q1, a cognitive performance test, and Q2, a proofreading task, at the L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K scenarios. Secsion 3 aimed to gather valuable participant feedback regarding their experiences with the lighting scenarios used in the experiments.

The study employed a unique approach due to the office layout and limited desk availability. The comprehensive study aimed to thoroughly investigate the impact of lighting conditions on occupants' cognitive performance, visual perception, and subjective experiences within an office setting. The deliberate variations in luminaire CCTs and the consideration of participant demographics contribute to the robustness of the study's findings.

5.2.1. Results of participants' lighting satisfaction study at phase 2

The comfort criteria of the participants are important in this study. H3 is the most preferred luminaire and succesful performanced height among H1, H2, and H3 at L1, but the performance of the participants is more successful at H2 of L2.

The lighting satisfaction survey was conducted at the conclusion of 4 scenarios of L1H3 3800K and L2H2 2700K, L2H2 3800K, and L2H2 6000K to confirm the effect of different CCTs in the study. Participants were asked to indicate their level of satisfaction by responding to the following statements: "I am satisfied with the lighting", "There is an appropriate level of illumination for the task I am currently performing" and "The color of the light is pleasant" and "The lighting is unified on the desk" and "The height of lighting is pleasant”. Additionally, they were requested to rate the lighting on a scale ranging from Uncomfortable to Comfortable, Not Uniform to Uniform, and Unsuitable to Suitable, taking into consideration the luminaire height.

5.2.2. Results of the observed performance and prevalence of L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H3 6000K

In terms of the performance level of the 24 participants, the highest performance was observed at L2H2 3800K, as indicated in Table 5.9. Participants achieved their best performance under L2H2 3800K compared to L1H3 3800K, L2H2 2700K, and L2H3 6000K scenarios. Therefore, the optimal scenario was determined to be L2H2 3800K based on the results of the visual performance tests conducted in Phase 1.

Furthermore, Figure 5.6 illustrates the participants' response times for Q1, indicating that the lowest values were recorded at L2H2 2700K compared to all other scenarios. Similarly, the response times for Q2 were found to be lowest at L2H2 3800K among all scenarios.

Figure 5.7 illustrates the participants' average error quantity for Q1, indicating that the lowest values were recorded at L2H2 2700K. For Q2, the lowest values were recorded at L2H2 6000K compared to other scenarios.

Table 5.9: Comparison of participants' performance for L1 3800K and L2 2700K L2 3800K, L2 6000K condition.

Luminaire scenarios	ERROR		Time	
	matching performance	visual proof	matching performance	visual proof
L1H3 3800K	✓✓	✓	✓	✓
L2H2 2700K	✓✓✓	✓✓	✓✓	✓✓
L2H2 3800K	✓✓	✓✓	✓✓✓	✓✓✓
L2H2 6000K	✓	✓✓✓	✓✓	✓✓

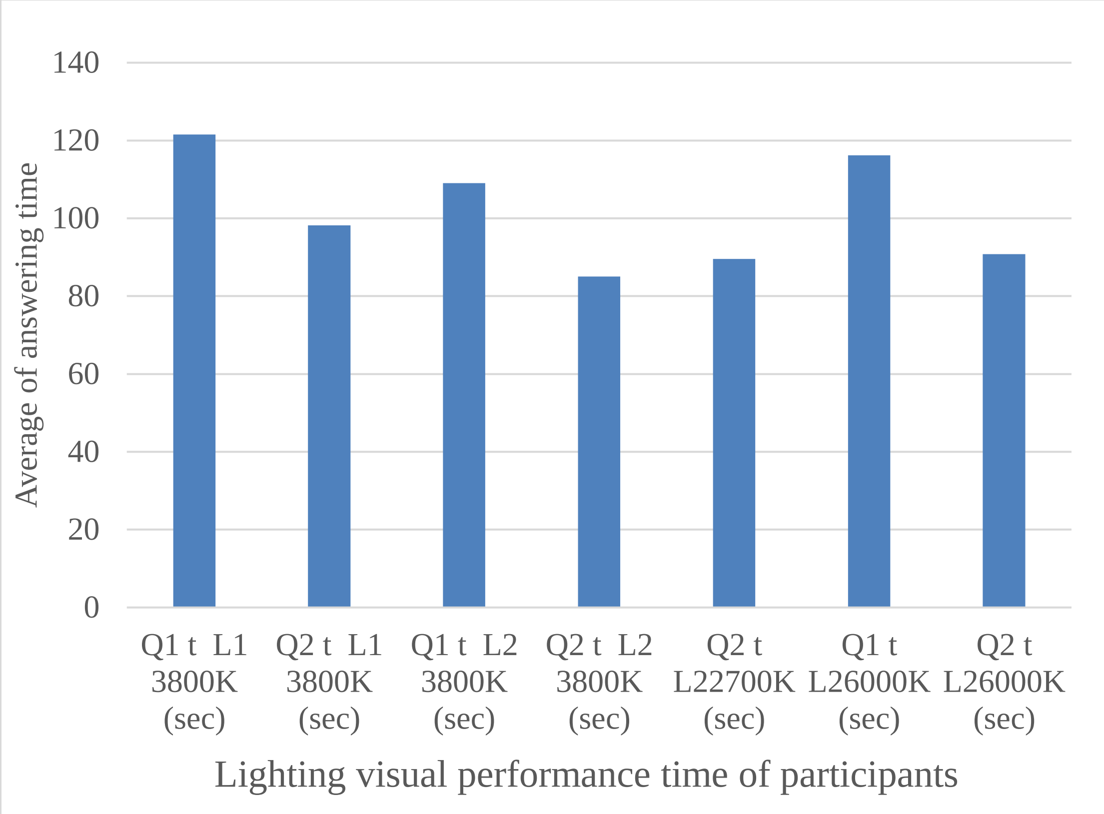


Figure 5.6: Performance report for L1 and L2 at Q1 and Q2 performing time on L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K.

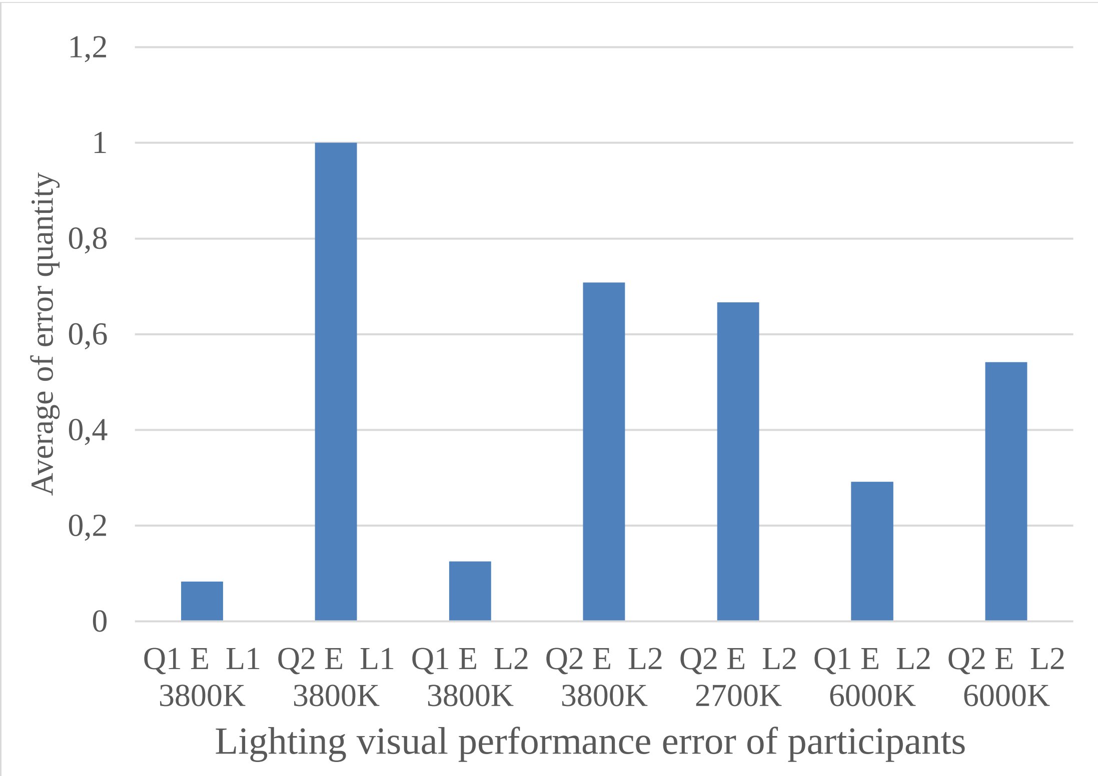


Figure 5.7: Performance report for L1 and L2 at Q1 and Q2 error quantity on L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K.

In Phase 2 of the study, it is crucial to consider the comfort criteria of the participants as a significant aspect. Despite the fact that L2H2 3800K demonstrates the highest level of performance compared to scenarios such as L1H3 3800K, L2H2 2700K, and L2H2 6000K, the response results to Q1 and Q2 are variable. However, in summary, L2H2 3800K derives the most successful condition among the four lighting scenarios. To evaluate the real impact of comfort criteria, it is essential to check the feedback preferences among participants.

The comprehensive analysis, documented in Table 5.10, revealed a list of statistically significant differences. These differences encompassed a wide array of metrics, including error quantities and answering time for the Q1 and Q2 at LH3 3800K, L2H2 2700K, L2H2 3800K, and L2H2 6000K.

Table 5.10: T-Test applied to test the difference between L1 and L2 lighting performances

Method	Description	P Value
T-Test	Paired T-Test and CI: Q1 E L1 3800K, Q1 E L2 3800K	0.714
	Paired T-Test and CI: Q1 t L1 3800K (sec), Q1 t L2 3800K (sec)	0.008
	Paired T-Test and CI: Q2 E L1 3800K, Q2 E L2 3800K	0.317
	Paired T-Test and CI: Q2 t L1 3800K (sec), Q2 t L2 3800K (sec)	0.004
	Paired T-Test and CI: Q1 E L2 3800K, Q1 E L2 2700K	0.426
	Paired T-Test and CI: Q1 t L2 3800K (sec), Q1 t L2 2700K (sec)	0.265
	Paired T-Test and CI: Q2 E L2 3800K, Q2 E L2 2700K	0.814
	Paired T-Test and CI: Q2 t L2 3800K (sec), Q2 t L2 2700K (sec)	0.405
	Paired T-Test and CI: Q1 E L2 2700K, Q1 E L2 6000K	0.11
	Paired T-Test and CI: Q1 t L2 2700K (sec), Q1 t L2 6000K (sec)	0.635
	Paired T-Test and CI: Q2 E L2 2700K, Q2 E L2 6000K	0.503
	Paired T-Test and CI: Q2 t L2 2700K (sec), Q2 t L2 6000K (sec)	0.753
	Paired T-Test and CI: Q1 E L2 3800K, Q1 E L2 6000K	0.357
	Paired T-Test and CI: Q1 t L2 3800K (sec), Q1 t L2 6000K (sec)	0.119
	Paired T-Test and CI: Q2 E L2 3800K, Q2 E L2 6000K	0.405
	Paired T-Test and CI: Q2 t L2 3800K (sec), Q2 t L2 6000K (sec)	0.136

It is observed that participants tend to express a greater level of comfort with L1H3 3800K, as highlighted in the data presented in Table 5.11. Conversely, the scenario that ranks the lowest in terms of participant comfort appears to be L2H2 6000K.

Overall, it can be inferred that the scenario with the highest level of satisfaction across all evaluation factors is L1H3 3800K. Figure 5.8 shows The pleasure rating reviews of participants at L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K. The blue color, signifying the L1H3 3800K scenario, prominently displays the highest column in terms of Satisfaction of Lighting. This suggests that lighting conditions are deemed adequate for task performance, with the color of light being visually appealing and uniformly distributed across the desk. Additionally, the mounting height of the lighting luminaires appears suitable for optimal illumination. Conversely, the column representing "Lighting unsatisfied you during task" indicates the lowest rating among the four scenarios, suggesting that participants found this lighting condition less conducive to task execution compared to the others.

Table 5.11: Comparison of the preference prevalence of participants between L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K scenarios.

Luminaire	CCT	Satisfaction of Lighting	There is appropriet lighting for the task	Color of light is appealing	Lighting unsatisfied you during task	Lighting is unified on desk	Lighting mountin height is suitable	Over all
L1	3800K	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
L2	3800K	✓✓	✓✓	✓✓	✓✓	✓✓	✓	✓✓
L2	2700K	✓✓✓	✓✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
L2	6000K	✓	✓	✓	✓	✓	✓✓	✓

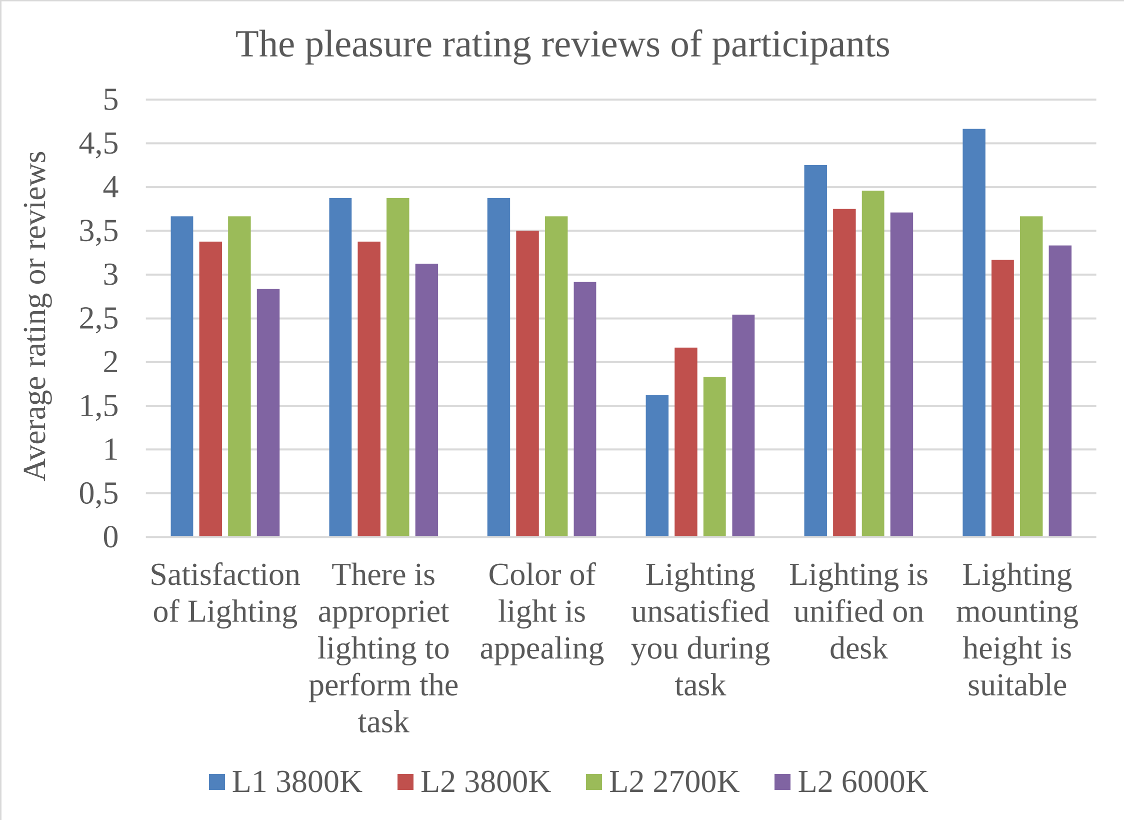


Figure 5.8: The pleasure rating reviews of participants at L1H3 3800K, L2H2 2700K, L2H2 3800K, L2H2 6000K.

Obviousely regarding the Table 5.11, it is shown that the most appealing scenarios are L1H3 3800K and L2H2 2700K which is summerized at Figure 5.9. Among four scenario, the best case between two different light destribution curve, is L2 2700K. In this case Figure 5.9 is shown to clarify the comparison of data of satisfication between L1H3 3800K and L2H2 2700K. The comparison between the L1H3 3800K and L2H2 2700K scenarios reveals notable differences in participants' perceptions of lighting satisfaction. While both scenarios received similar ratings for the satisfaction of lighting and adequacy of task lighting, participants expressed a higher level of dissatisfaction with the lighting in the L2H2 2700K scenario. This suggests that the warmer color temperature of 2700K may not have been as conducive to task performance as the cooler 3800K in the L1H3 scenario.

Furthermore, the color of light in the 3800K scenario was deemed much more appealing, indicating a preference for the cooler temperature. Additionally, participants noted that the lighting in the L1H3 3800K scenario was more uniformly distributed across the desk compared to the L2H2 2700K scenario, where it may have been less consistent.

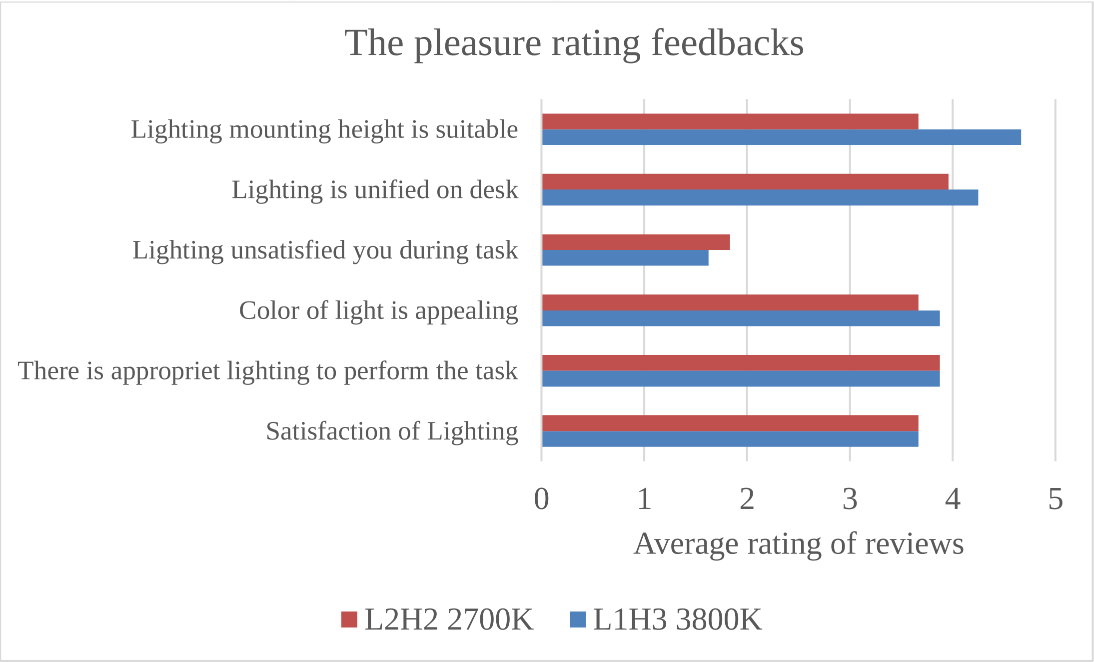


Figure 5.9: The pleasure rating reviews of participants at L1H3 3800K, L2H2 2700K.

5.2.3. Statistical results of participants' preference between L2H2 2700K, L2H2 3800K, L2H2 6000K and L1H3 3800K

In examining the efficacy of various lighting scenarios, with a particular focus on L1H3 and L2H2, the study aimed to elucidate disparities in variuse CCTs across different lighting setups and to gauge participants' preferences. Notably, the investigation found L1H3 to emerge as the most favored scenario, while L2H2, featuring a CCT of 3800K, demonstrated notable success in terms of performance metrics.

Employing Pearson correlation analysis on the dataset, the study utilized the p-value as a critical metric to ascertain the statistical significance of observed correlations. This statistical approach was instrumental in elucidating the strength and direction of relationships between various variables. A p value falling below the predetermined significance threshold underscored the presence of meaningful correlations between the variables under examination.

The comprehensive analysis, documented in Table 5.12, and Table 5.13 revealed a list of statistically significant differences. These differences encompassed a wide array of metrics, including satisfaction level with lighting, suitable illuminance level on the desk, uniformity of lighting, pleasantness of light color, unpleasantness of lighting during tests, and the height of lighting between the lighting scenarios of phase 2.

Table 5.12: The Pearson correlation of the comments of the lighting scenarios are presented.

Description	P Value
Correlations: Satisfaction of lighting L1H3 3800K, L2H2 3800K	0.344
Correlations: Satisfaction of lighting L1H3 3800K, L2H2 2700K	0.389
Correlations: Satisfaction of lighting L1H3 3800K, L2H2 6000K	0.223
Correlations: Satisfaction of lighting L2H2 3800K, L2H2 2700K	0.843
Correlations: Satisfaction of lighting L2H2 3800K, L2H2 6000K	0.075
Correlations: Satisfaction of lighting L2H2 2700K, L2H2 6000K	0.399
Correlations: There is appropriet lighting for the task L1H3 3800K, L2H2 3800K	0.11
Correlations: There is appropriet lighting for the task L1H3 3800K, L2H2 2700K	0.002

Table 5.12 (continued): The Pearson correlation of the comments of the lighting scenarios are presented.

Description	P Value
Correlations: There is appropriet lighting for the task L1H3 3800K, L2H2 6000K	0.076
Correlations: There is appropriet lighting for the task L2H2 3800K, L2H2 2700K	0.285
Correlations: There is appropriet lighting for the task L2H2 3800K, L2H2 6000K	0.188
Correlations: There is appropriet lighting for the task L2H2 2700K, L2H2 6000K	0.802
Correlations: Color of light is appealing L1H3 3800K, L2H2 3800K	0.024
Correlations: Color of light is appealing L1H3 3800K, L2H2 2700K	0.193
Correlations: Color of light is appealing L1H3 3800K, L2H2 6000K	0.056
Correlations: Color of light is appealing L2H2 3800K, L2H2 2700K	0.898
Correlations: Color of light is appealing L2H2 3800K, L2H2 6000K	0
Correlations: Color of light is appealing L2H2 2700K, L2H2 6000K	0.821
Correlations: Lighting unsatisfied you during task L1H3 3800K, L2H2 3800K	0.587
Correlations: Lighting unsatisfied you during task L1H3 3800K, L2H2 2700K	0.081
Correlations: Lighting unsatisfied you during task L1H3 3800K, L2H2 6000K	0.5
Correlations: Lighting unsatisfied you during task L2H2 3800K, L2H2 2700K	0.348
Correlations: Lighting unsatisfied you during task L2H2 3800K, L2H2 6000K	0
Correlations: Lighting unsatisfied you during task L2H2 2700K, L2H2 6000K	0.016
Correlations: Lighting height is appealing L1H3 3800K, L2H2 3800K	0.118
Correlations: Lighting height is appealing L1H3 3800K, L2H2 2700K	0.038
Correlations: Lighting height is appealing L1H3 3800K, L2H2 6000K	0.087
Correlations: Lighting height is appealing L2H2 3800K, L2H2 2700K	0.044
Correlations: Lighting height is appealing L2H2 3800K, L2H2 6000K	0
Correlations: Lighting height is appealing L2H2 2700K, L2H2 6000K	0.156

Table 5.13: T-Test for participants' feedback on lighting scenarios between L1H3 3800K, L2H2 3800K, L2H2 2700K, and L2H2 6000K.

Method	Description	P Value
T-Test	Paired T-Test and CI: Satisfaction of Lighting of L1H3 3800K- L2H2 3800K	0.245
	Paired T-Test and CI: There is appropriet lighting for the task L1H3 3800K- L2H2 3800K	0.011
	Paired T-Test and CI: Color of light is appealing L1H3 3800K- L2H2 3800K	0.153
	Paired T-Test and CI: Lighting unsatisfied you during task L1H3 3800K- L2H2 3800K	0.056
	Paired T-Test and CI: Lighting is unified on desk L1H3 3800K- L2H2 3800K	0.001
	Paired T-Test and CI: Lighting mountin height is suitable L1H3 3800K- L2H2 3800K	0.001
	Paired T-Test and CI: Satisfaction of Lighting of L1H3 3800K- L2H2 2700K	1
	Paired T-Test and CI: There is appropriet lighting for the task L1H3 3800K- L2H2 2700K	1
	Paired T-Test and CI: Color of light is appealing L1H3 3800K- L2H2 2700K	0.435
	Paired T-Test and CI: Lighting unsatisfied you during task L1H3 3800K- L2H2 2700K	0.364
	Paired T-Test and CI: Lighting is unified on desk L1H3 3800K- L2H2 2700K	0.05
	Paired T-Test and CI: Lighting mountin height is suitable L1H3 3800K- L2H2 2700K	0.011
	Paired T-Test and CI: Satisfaction of Lighting of L1H3 3800K- L2H2 6000K	0.003
	Paired T-Test and CI: There is appropriet lighting for the task L1H3 3800K- L2H2 6000K	0.004
	Paired T-Test and CI: Color of light is appealing L1H3 3800K- L2H2 6000K	0
	Paired T-Test and CI: Lighting unsatisfied you during task L1H3 3800K- L2H2 6000K	0.007
	Paired T-Test and CI: Lighting is unified on desk L1H3 3800K- L2H2 6000K	0.02
	Paired T-Test and CI: Lighting mountin height is suitable L1H3 3800K- L2H2 6000K	0.003
	Paired T-Test and CI: Satisfaction of Lighting of L2H2 3800K- L2H2 2700K	0.317
	Paired T-Test and CI: There is appropriet lighting for the task L2H2 3800K- L2H2 2700K	0.037
	Paired T-Test and CI: Color of light is appealing L2H2 3800K- L2H2 2700K	0.647
	Paired T-Test and CI: Lighting unsatisfied you during task L2H2 3800K- L2H2 2700K	0.257
	Paired T-Test and CI: Lighting is unified on desk L2H2 3800K- L2H2 2700K	0.057

Table 5.13 (continued): T-Test for participants' feedback on lighting scenarios between L1H3 3800K, L2H2 3800K, L2H2 2700K, and L2H2 6000K.

T-Test	Paired T-Test and CI: Lighting mountin height is suitable L2H2 3800K- L2H2 2700K	0.266
	Paired T-Test and CI: Satisfaction of Lighting of L2H2 6000K- L2H2 2700K	0.007
	Paired T-Test and CI: There is appropriet lighting for the task L2H2 6000K- L2H2 2700K	0.021
	Paired T-Test and CI: Color of light is appealing L2H2 6000K- L2H2 2700K	0.023
	Paired T-Test and CI: Lighting unsatisfied you during task L2H2 6000K- L2H2 2700K	0.014
	Paired T-Test and CI: Lighting is unified on desk L2H2 6000K- L2H2 2700K	0.299
	Paired T-Test and CI: Lighting mountin height is suitable L2H2 6000K- L2H2 2700K	0.491
	Paired T-Test and CI: Satisfaction of Lighting of L2H2 3800K- L2H2 6000K	0.045
	Paired T-Test and CI: There is appropriet lighting for the task L2H2 3800K- L2H2 6000K	0.354
	Paired T-Test and CI: Color of light is appealing L2H2 3800K- L2H2 6000K	0.01
	Paired T-Test and CI: Lighting unsatisfied you during task L2H2 3800K- L2H2 6000K	0.071
	Paired T-Test and CI: Lighting is unified on desk L2H2 3800K- L2H2 6000K	0.846
	Paired T-Test and CI: Lighting mountin height is suitable L2H2 3800K- L2H2 6000K	0.575

6. CONCLUSIONS AND RECOMMENDATIONS

This study investigates the impact of human centered lighting in an open plan office environment at Istanbul Technical University. Sixty participants were involved in phase one, followed by twenty four in phase two. The aim was to assess individual lighting solutions while meeting Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) metrics. Phase one used single Correlated Color Temperature (CCT) LED sources, and phase two explored different CCTs. Preliminary findings showed potential for energy efficient lighting modifications. Phase two aimed to optimize lighting quality, considering comfort criteria. Overall, the study suggests integrating individualized lighting systems for open plan offices, aligning with HCL requirements and ensuring worker satisfaction.

In the design development phase, the lighting design process was outlined, along with summaries of pertinent circadian lighting metrics, simulation tools, energy considerations, and the research plan for the circadian lighting open plan office. Meeting the necessary EV levels at eye level for occupants posed challenges, particularly with traditional ceiling recessed luminaire technology. Limited optical distributions and color tuning options restricted the selection of luminaires meeting the desired experimental lighting conditions. Designing to align with recommended thresholds of CS and EML throughout the open plan office ensured horizontal and vertical illuminance levels consistent with recommendations from the IES for visual tasks. The experimental aspect of open plan office lighting for circadian impact and the investigation of occupant responses to office lighting are discussed within the context of a field study. This field holds significant importance for exploration within actual office environments, as alterations in workplace layouts can influence how researchers interpret prior discoveries regarding office lighting and its potential impacts on occupants' comfort creteria. It's crucial to comprehend the role of office lighting within the wider context of environmental factors in the office and to consider human behavior beyond the office for a comprehensive understanding of its potential influence. Despite the notable increase in brightness during the day, the traditional goals of office lighting, particularly how occupants subjectively perceive the environment and their visual task demands, continue to be paramount.

Regarding the simulation study, two different light distribution curve luminaires, Direct Suspended Linear (L1) and Direct and Indirect Suspended Linear (L2), were chosen. Additionally, threshold suspended mounting heights of 1.5m (H1) and 2.3m (H3), and one Optimum Luminaire Height (OLH) of 1.8m (H2) above the finished floor were defined for the lighting luminaires. The experimental aspect involved assessing changes in lighting levels, psychological comfort, and performance at three main target heights (H1, H2, H3) for both lighting scenarios (L1 and L2). Regarding the adjustable height of luminaires and lighting scenarios, changes in lighting levels, psychological comfort, and performance were examined by using three main target height, H1, H2, H3 values on both L1 and L2. To assess the impact of lighting level changes on psychological comfort, participants were asked a series of questions in six different lighting scenarios for office environments at first phase of study. The study conducted an experiment in a setup considered "appropriate" for exploring human centered lighting conditions in addition to physiological comfort conditions. Questionaire 1 which is visual cognitive matching performance test (Q1) and questionaire 2 which is visual proofreading task test (Q2) are queried for each participant during the survey, while error (E) quantities and consumed time (t) periods serve as measurement scales, alongside the occupants' preferences based on their comfort criteria. The results, focusing on light levels, luminaire positions, and light distribution curves, are summarized as follows:

- Matching performance and visual perception of participants of p values on L1H1 Q1 with a p value of 0.04, L1H1 Q2 E with a p value of 0.03, L2H2 Q1 t with a p value of 0.02, L2H2 Q2 E with a p value of 0.04, L2H2 Q2 t with a p value of 0.01, L1H3 Q2 t with a p value of 0.02, among gender, eye disorder, and age factors is accepted. Moreover, L1H2 Q1 E eye disorder with a p value of 0.01.

✓ These findings reject the null hypothesis that age and eye disorders have no effect on the performance of participants. This indicates that both age and the presence of eye disorders significantly influence how well participants perform, suggesting a meaningful relationship between these variables and participant performance.

- The performance evaluation results of participants were compared between H1, H2, and H3. For L1, the p values for H1 and H3 Q1 t were 0.024, H1 and H3 Q2 t were 0.012, and H2 and H3 Q2 t were 0.011. For L2, the p values for H1 and H2 Q1 E were 0.028, H1 and H3 Q2 E were 0.008, and H2 and H3 Q2 E were 0.036.

✓ These p values reject the null hypotheses that there is no difference in performance with respect to the variation in the heights of L1 and L2. This implies that the differences in heights between L1 and L2 significantly affect performance, indicating that height variation is an important factor in determining performance outcomes.

- The impact of difference on L1 and L2 with the point of view of performance in H1, H2, and H3 was measured. According to the test results at a significance level of p value lower than 0.05, significant differences were found in response times for Q1 in L1H1, L2H1, and Q2 in L1H2, L2H2.

✓ It shows that the difference in performance between L1 and L2 is statistically significant. This indicates that the variation in performance levels between L1 and L2 is not due to random chance but rather suggests a meaningful difference. As a result, the performance metrics for L1 and L2 should be considered distinct and not equivalent.

- The comparison of participants performance results between H1, H2, H3, performed on Q1 t and Q2 t, shows that the null hypotheses are rejected for H1 and H2, but approved for H3.

✓ It shows that the difference in performance of participants at H1 and H2 is rejected due to similar results, but the difference in performance is approved for H3. This indicates that there is no significant difference in performance between H1 and H2, as their results are comparable. However, there is a statistically significant difference in performance at H3, suggesting that H3 impacts performance differently than H1 and H2.

- The relationship between gender and visual disorder with performance based on changes in light levels was not significant at a significance level of p value 0.05.

- The age factor showed a significant relationship with performance based on changes in light levels, specifically between the age groups 20-30 and 30-40, as well as between the age groups 20-30 and 40 and above.

✓ This indicates that variations in light levels affect the performance of participants differently depending on their age, with notable differences observed between the younger (20-30) and older age groups (30-40 and 40 and above).

- The responses due to the tests indicated that L1H3 and L2H2 were considered the most successful cases.

- L1 received higher preference at all three heights due to differences in the lighting distribution curve. The test results showed that perceived differences in lighting levels influenced personal impressions of psychological comfort. Improvements in physical comfort conditions, such as a higher height of lighting, were viewed positively, indicating that both the quality and placement of lighting significantly affect user comfort and preference.

- Uniformity was achieved in both L1 and L2 at H1, but a worse situation was noted at H2, where the level of uniformity was lower compared to other scenarios.

- According to the study results, a generalization such as "increasing light levels improves performance" cannot be settled. Test results indicate that L1H3 and L2H2 are the most successful scenarios. L1H3 has EH: 752 lux, EV: 550 lux, and L2H2 has EH: 520 lux, EV: 393 lux, meeting minimum CS and EML values.

✓ It shows that by meeting the minimum requirements of the target, we can achieve the HCL necessities. In terms of satisfaction, participants expressed the highest satisfaction in scenarios L1H3 and L2H3.

- A key finding of this study was the high performance achieved in the L1H3 and L2H2 configurations. For the H2 setting, we proposed a 40% power saving for both L1 and L2. However, our energy efficient lighting plan, based on the luminaire distribution curve and SPD of the lights, was ignored in L1H3 due to participants' feedback and performance. On the other hand, the L2H2 configuration showed good performance, but participants were less satisfied with it. This shows the challenge of balancing energy efficiency and user satisfaction in lighting design. While L2H2 met performance goals, it didn't fully meet users' comfort and preferences, highlighting the need to consider both technical and human factors in future lighting designs.

- The performance of office workers is highly dependent on age groups, as recorded in the test results. These findings align with the performance situation in L1H3, where energy efficiency was not achieved. While the satisfaction rate is higher in L2H3, participants performed better in L2H2, where energy efficiency gains significance. Therefore, between L1H3 and L2H2, participant satisfaction with light levels, given adequate light levels and uniformity on the working desk, was found to be significant.

At the phase 2, L1 is assessed with a constant CCT of 3800K, operating at 100% due to approved height at phase 1 of the study at H3 (2.3m above the finished floor). Meanwhile, L2 is examined with different CCTs 2700K, 3800K, and 6000K each set at operation rates of 75%, 60%, and 40% of the total luminaire output, respectively. It's noteworthy that these configurations are designed to meet the minimum CS requirement of 0.3. Regarding EML values, L1 has an EML set at 358, whereas L2 exhibits varied results for CCTs: EML of 275.5 for 2700K, EML of 293 for 3800K, and EML of 319 for 6000K. The objective of this phase is to investigate the influence of variable CCTs on visual comfort and circadian response within the office setting. The analysis of workplace lighting studies for daytime workers involves examining how occupants respond to varying levels of illuminance and combinations of spectrum and illuminance. Accordingly, twenty four participants, characterized as office workers, completed visual performance tests and provided assessments regarding their alertness, mood, lighting, environmental satisfaction, and feelings of sleepiness.

- The findings from Phase 2 of the study indicate that some office occupants expressed dissatisfaction with the lighting set at 6000K. Many participants found this CCT to be too harsh and unnatural for a comfortable working environment. This feedback suggests that while 6000K lighting may be efficient in certain contexts, it may not always align with occupant preferences for a more pleasant and productive workspace. Consequently, it highlights the need to consider a balance between energy efficiency and occupant comfort when selecting lighting solutions.

- The warmer CCT of 2700K in the L2H2 configuration likely had a positive impact on participants, as the dimming rate was sufficiently low to meet the CS and

EML requirements. This resulted in higher illuminance levels on the desk compared to the scenarios with L2H2 3800K and L2H2 6000K. The favorable response to the 2700K lighting indicates that warmer CCTs can enhance both the visual and non visual benefits of lighting, promoting a more comfortable and effective work environment.

- Statistically significant correlations were observed regarding appropriate lighting for the task between L1H3 3800K and L2H2 2700K, with a p value of 0.002. Similarly, statistically significant correlations were observed regarding the appealing color of light between L1H3 3800K and L2H2 3800K, with a p value of 0.024, and between L2H2 3800K and L2H2 6000K, with a p value of 0.

✓ The findings show that participants' preferences for L1H3 at 3800K and L2H2 at 2700K are similar. Participants' feedback on the color of light for both L1H3 and L2H2 configurations indicated no significant difference between 3800K and 6000K in the L2H2 scenario. This suggests that, for these participants, the specific color temperature within the given range does not affect their satisfaction or perception of the lighting quality.

- Regarding lighting dissatisfaction during tasks, statistically significant correlations were observed between L2H2 3800K and L2H2 6000K, with a p value of 0, and between L2H2 2700K and L2H2 6000K, with a p value of 0.016. Participants reported dissatisfaction with both 2700K and 6000K in the L2H2 configuration.

✓ This indicates that the extremes of the color temperature spectrum, both warmer 2700K and cooler 6000K, were less favored by participants, highlighting the importance of selecting an optimal CCT that balances both performance and user comfort.

- Additionally, correlations on lighting height preferences between L1H3 3800K and L2H2 2700K, L2H2 3800K and L2H2 2700K, and L2H2 3800K and L2H2 6000K were significant, with p values of 0.038, 0.044, and 0, respectively.

✓ The lighting mounting height appears to be comfortable across all scenarios, as confirmed by the fact that the most comfortable configurations were selected based on the results from Phase 1. This suggests that the chosen mounting heights were effective in providing optimal lighting conditions that met the participants' comfort requirements.

- Participants clearly preferred H3 over H2 due to its more appealing lighting conditions. This indicates that, for suspended luminaires, managing the height to achieve the target height is crucial in order to maintain the advantages of CS and EML. Proper height management ensures that the lighting not only meets technical requirements but also enhances user satisfaction and comfort.

- These results indicate that future research should examine furniture arrangements in office spaces to improve illuminance levels through lighting design. Additionally, advocating for suspended mounting designs to reduce the number of luminaires is crucial. Suspended lighting solutions require dynamic height adjustments to optimize luminaire SPD types for the expected illuminance.

- Using consistent survey questions across different lighting concepts can help identify the specific factors influencing different CCTs preferences.

- Furthermore, it is proposed to develop an energy efficient system by integrating individualized lighting tailored for open-plan office workers. Such a system not only aligns with HCL requirements but also enhances office worker satisfaction. The findings confirm the most acceptable lighting scenario for openplan offices, providing valuable insights for future research in this field. Moreover, these findings can be integrated into office lighting automation systems, enabling the creation of efficient, adaptive setups tailored to individual office occupants' needs. By leveraging these insights, lighting systems can be personalized to enhance both comfort and productivity, ensuring that each person receives optimal lighting conditions for their specific tasks and preferences.

As a recommendation, our case study investigation encountered several challenges commonly associated with field research endeavors. Specifically, our study relied solely on self reported subjective evaluations as questionaires and surveys, as objective data collection methods like wearable health trackers were not implemented. It's essential to recognize that self reported evaluations may not always perfectly align with objective physiological measures of quality. However, obtaining physiological data such as urine, blood, or saliva samples would have required significant investments in terms of time, finances, and manpower. Additionally, our data analysis did not consider various confounding variables, such as the potential effects of exercise, caffeine intake, exposure to daylight during the day, sleep quality, and the regulation of circadian rhythms.

For future work, it could be noteworthy to integrate the effect of daylight into indoor lighting systems to enhance the requirements for CS and EML. Integrating daylight conditions, along with the findings of this study, could improve the environment for office workers and guarantee energy savings by reducing reliance on artificial lighting. By continuing to explore and refine these approaches, future research can provide valuable insights and practical solutions for optimizing indoor lighting in a way that benefits office workers.

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APPENDICES

APPENDIX A: The SPDs of the luminaires used in the study, as well as all simulation results that were conducted and repeated to clarify the experimental phase.

APPENDIX B: The questionnaire and all survey documents provided to the participants.

APPENDIX A

Table A.1: Luminaire list that proposed for lighting design at open plan office

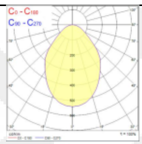
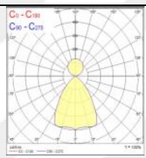
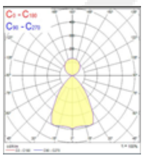
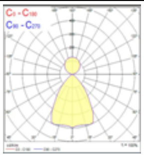
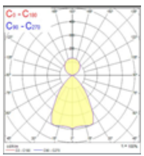
Luminaire Name	Luminaire photo	Light distribution curve	Total power consumption (W)	Luminaire luminous Flux (lm)	Luminaire efficacy (lm/W)	Colour Temperature (K)	Melanopic Ratio
SQUARE RECESSED 325X325			12	1350	113	4000	0.718
LINEAR SUSPENDED 20X1200 2700K %20			34	3500	103	2700	0.475
LINEAR SUSPENDED 20X1200 2700K %50			34	3500	103	2700	0.468
LINEAR SUSPENDED 20X1200 2700K %100			34	3500	103	2700	0.465
LINEAR SUSPENDED 20X1200 3800K %20			34	3500	103	3800	0.725

Table A.1 (continued): Luminaire list that proposed for lighting design at open plan office.

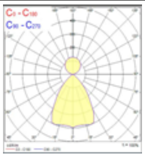
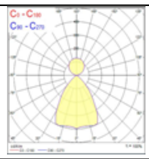
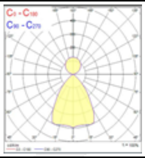
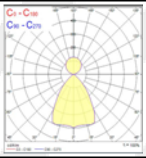
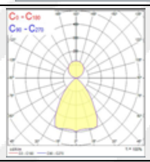
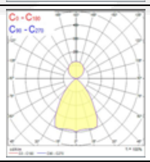
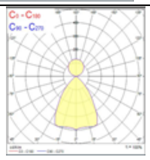
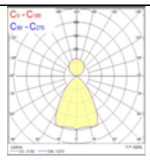
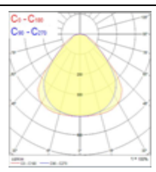
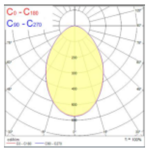
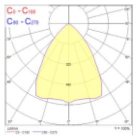
LINEAR SUSPENDED 20X1200 3800K %50			34	3500	103	3800	0.731
LINEAR RECESSED 100% 20X1200			34	3500	103	3900	0.88
LINEAR SUSPENDED 20X1200 5000K %20			34	3500	103	5000	0.887
LINEAR SUSPENDED 20X1200 5000K %50			34	3500	103	5000	0.886
LINEAR SUSPENDED 20X1200 5000K %100			34	3500	103	5000	0.88
LINEAR SUSPENDED 20X1200 6000K %20			34	3500	103	6000	0.966
LINEAR SUSPENDED 20X1200 6000K %50			34	3500	103	6000	0.967
LINEAR SUSPENDED 20X1200 6000K %100			34	3500	103	6000	0.967
PANEL 600			38	3225	88	3000	0.447

Table A.1 (continued): Luminaire list that proposed for lighting design at open plan office.

ROUND RECESSED 220X220			21	1989	95	4000	0.623
LINEAR RECESSED 1200			27	3400	126	4000	0.656

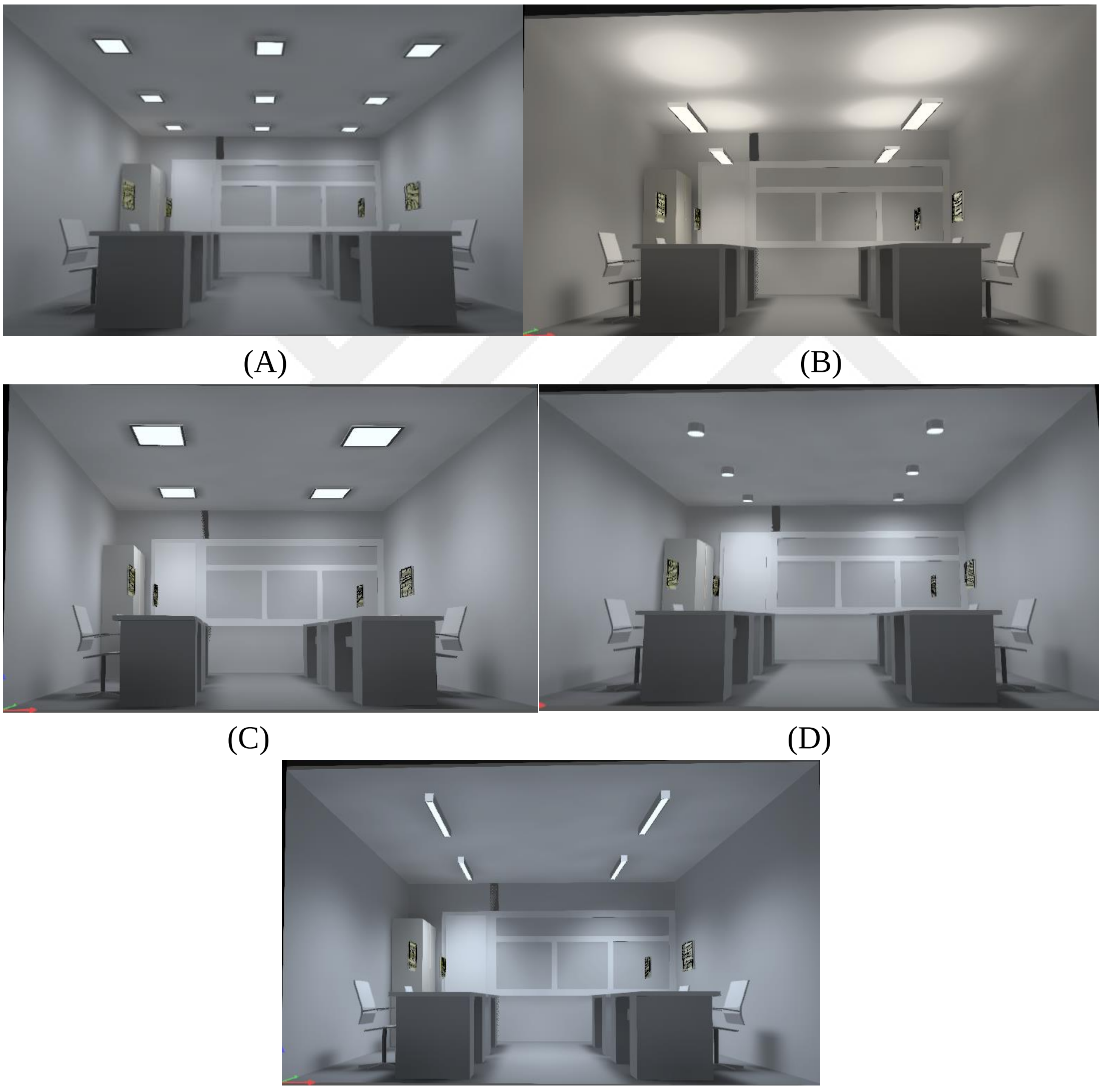


Figure A.1: Sample luminaire placement and mounting grid for A: SQUARE RECESSED 325X325, B: LINEAR D/I SUSPENDED 20X1200 2700K %20, C: PANEL 600, D: ROUND RECESSED 220X220, E: LINEAR RECESSED 1200.

Table A.2: Detail of the lighting design for open plan office with 4 occupant desk.

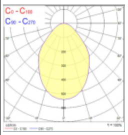
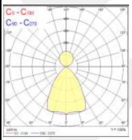
Luminaire Name		Luminaire photo	Light distribution curve	Total power consumption (W)	Luminaire luminous Flux (lm)	Luminaire efficacy (lm/W)	Colour Temperature (K)	Melanopic Ratio	EH Room (lux) (H:0.8m)	EH Desk1 (lux)	EV Desk User1 (lux)	Circadian Stimulus Desk1	Equivalent Melanopic Lux	Luminaire quantity
A	SQUARE RECESSED 325X325			12	1350	113	4000	0.718	323	334	146	0.132	104.82	9
B	LINEAR SUSPENDED 20X1200 2700K %20			34	3500	103	2700	0.475	23	30.9	20	0.024	9.5	4
B	LINEAR SUSPENDED 20X1200 2700K %50			34	3500	103	2700	0.468	120	134	60.6	0.075	28.36	4
B	LINEAR SUSPENDED 20X1200 2700K %100			34	3500	103	2700	0.465	331	472	334	0.384	155.31	4

Table A.2 (continued) : Detail of the lighting design for open plan office with 4 occupant desk.

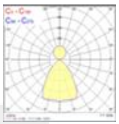
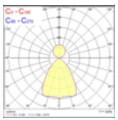
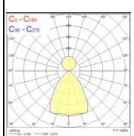
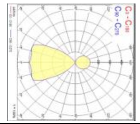
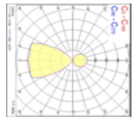
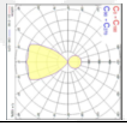
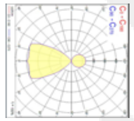
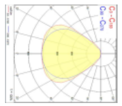
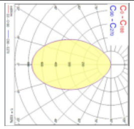
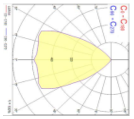
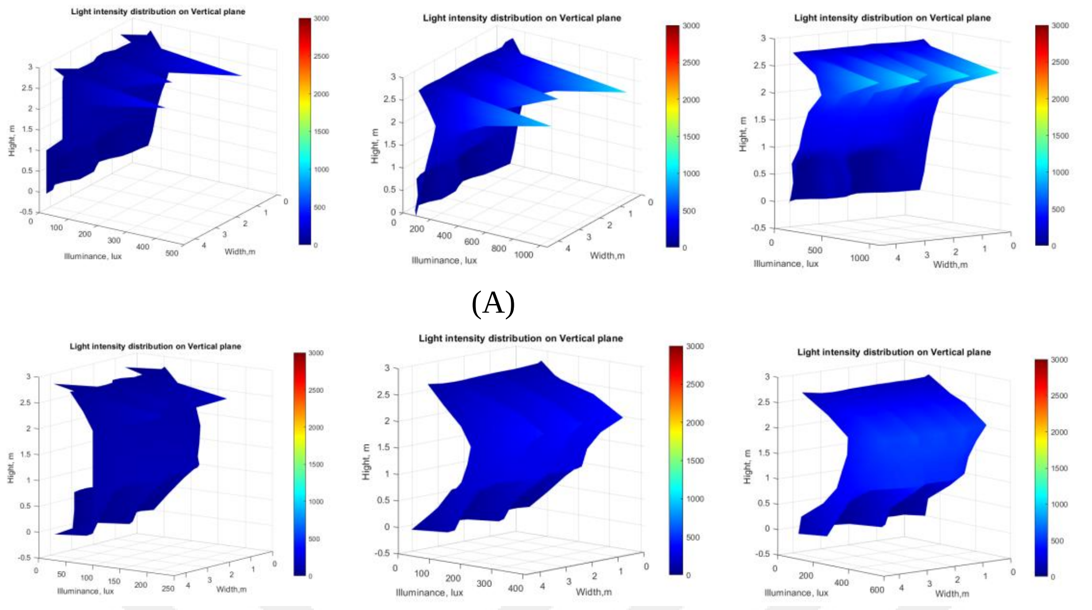
B	LINEAR SUSPENDED 20X1200 3800K %20			34	3500	103	3800	0.725	23.4	33.4	23.6	0.023	17.11	4
B	LINEAR SUSPENDED 20X1200 3800K %50			34	3500	103	3800	0.731	169	242	170	0.167	124.27	4
B	LINEAR RECESSED 100% 20X1200			34	3500	103	3900	0.88	357	510.00	361	0.29	317.68	4
B	LINEAR SUSPENDED 20X1200 5000K %20			34	3500	103	5000	0.887	24.2	24.4	34.4	0.05	30.51	4
B	LINEAR SUSPENDED 20X1200 5000K %50			34	3500	103	5000	0.886	172	246	173	0.23	153.27	4

Table A.2 (continued) : Detail of the lighting design for open plan office with 4 occupant desk.

B	LINEAR SUSPENDED 20X1200 5000K %100			34	3500	103	5000	0.88	363	518	367	0.38	322.96	4
B	LINEAR SUSPENDED 20X1200 6000K %20			34	3500	103	6000	0.966	25	35.7	25.2	0.05	24.34	4
B	LINEAR SUSPENDED 20X1200 6000K %50			34	3500	103	6000	0.967	176	251	177	0.27	171.15	4
B	LINEAR SUSPENDED 20X1200 6000K %100			34	3500	103	6000	0.967	362	517	364	0.41	351.98	4
C	PANEL 600			38	3225	88	4000	0.447	357	390	201	0.21	89.84	4
D	ROUND RECESSED 220X220			21	1989	95	4000	0.623	330	365	147	0.11	91.58	6
E	LINEAR RECESSED 1200			27	3400	126	4000	0.656	428	485	219	0.16	143.66	4

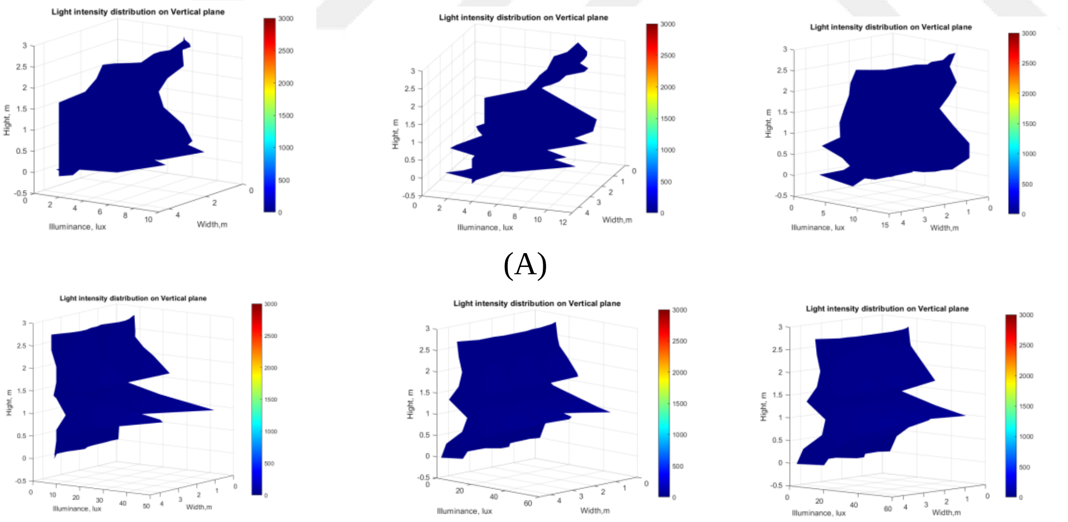
Target 300 lux Target 500 lux Target 750 lux



(B)

Figure A.2: SQUARE RECESSED 325X325: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux

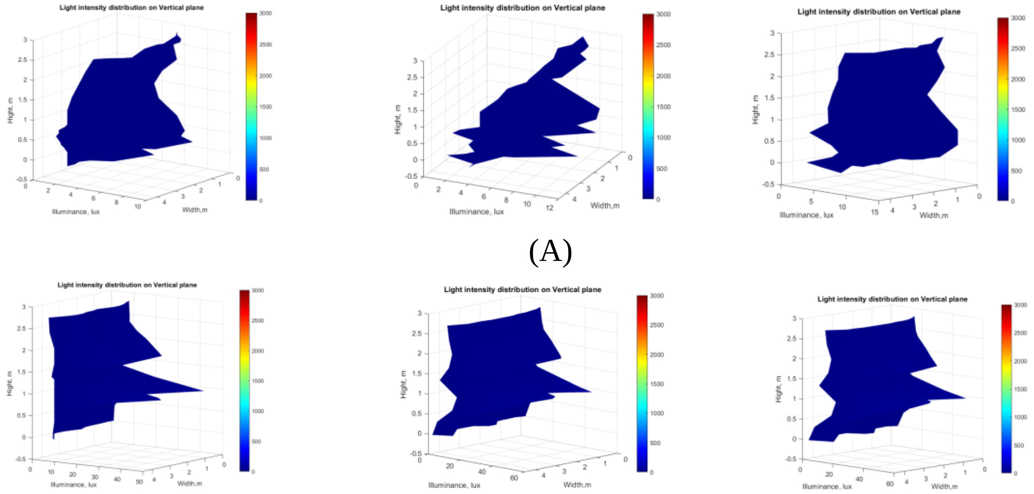
Target 300 lux Target 500 lux Target 750 lux



(B)

Figure A.3: LINEAR SUSPENDED D/I 20X1200 2700K %20: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux

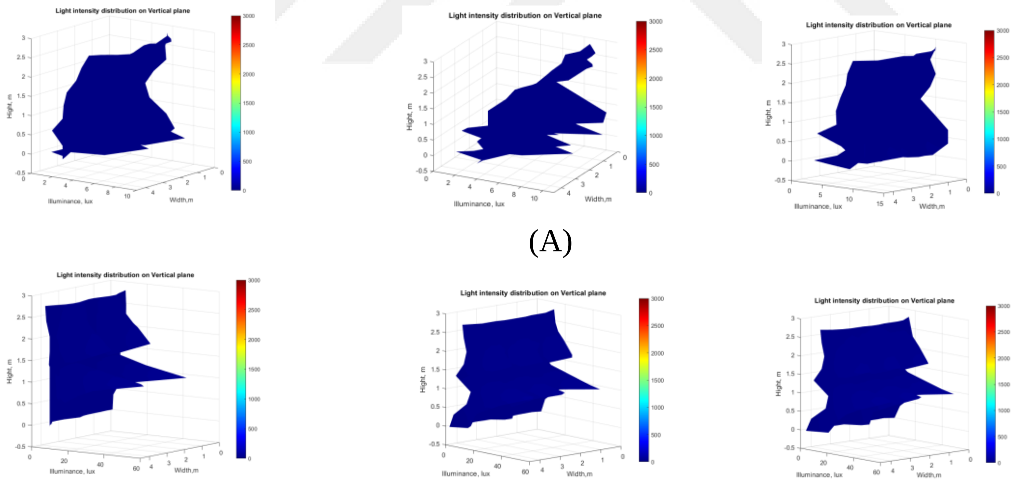


(A)

(B)

Figure A.4: LINEAR SUSPENDED D/I 20X1200 2700K %20: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux

Target 300 lux Target 500 lux Target 750 lux



(A)

(B)

Figure A.5: LINEAR SUSPENDED D/I 20X1200 5000K %20: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

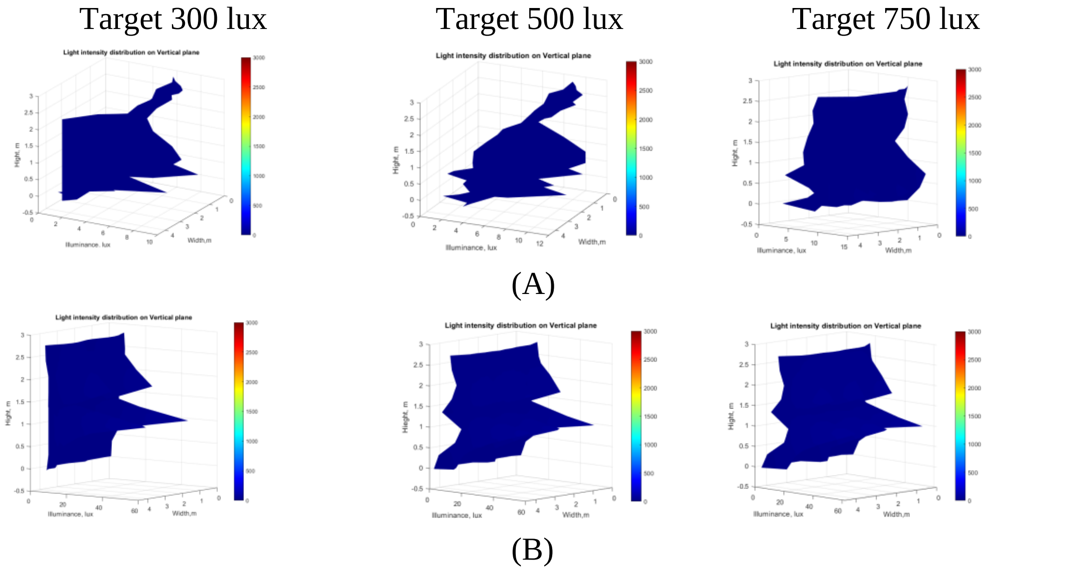


Figure A.6: LINEAR SUSPENDED D/I 20X1200 6000K %20: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux

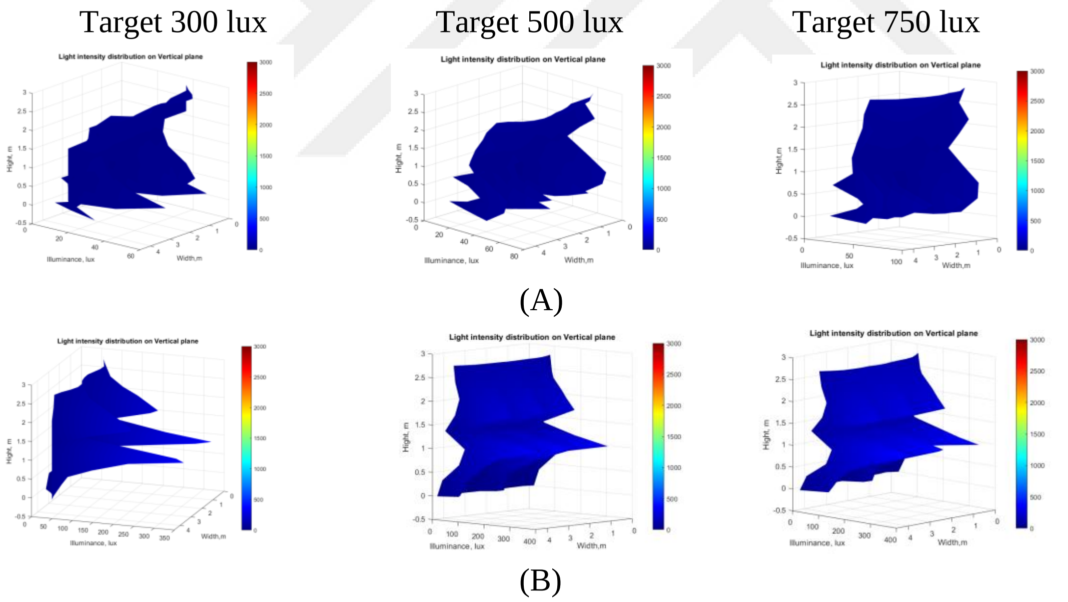


Figure A.7: LINEAR SUSPENDED D/I 20X1200 2700K %50: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux

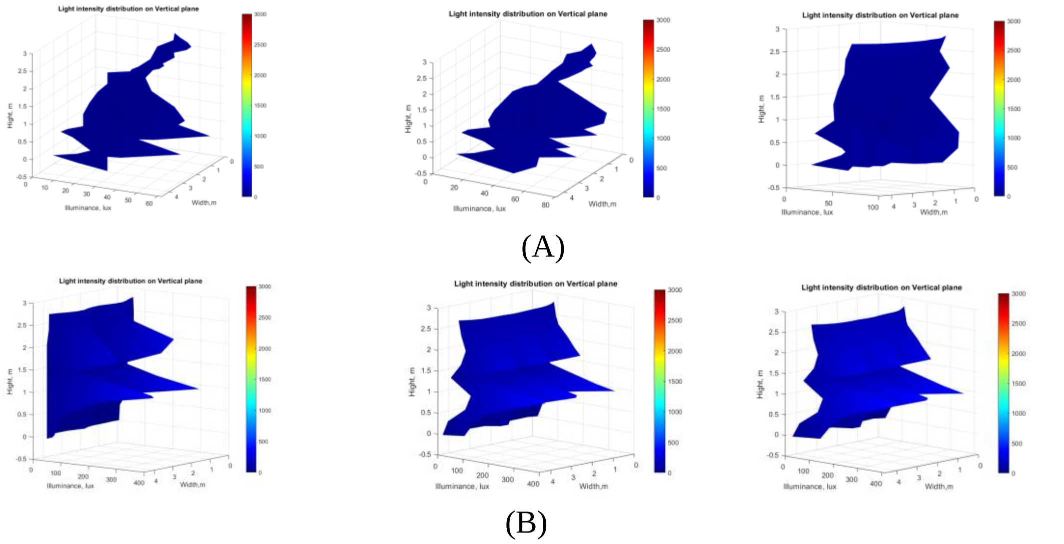


Figure A.8: LINEAR SUSPENDED D/I 20X1200 3800K %50: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux

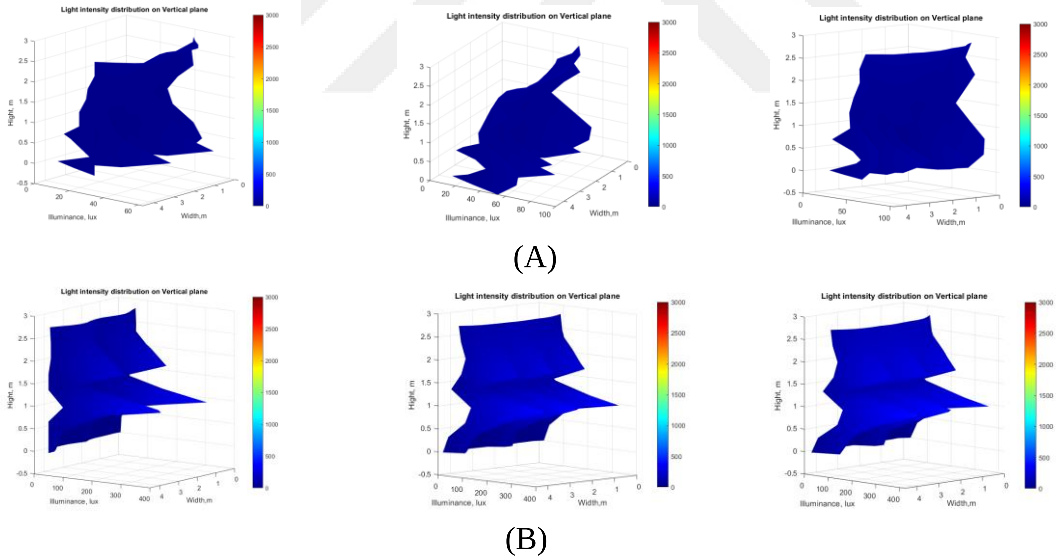


Figure A.9: LINEAR SUSPENDED D/I 20X1200 5000K %50: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

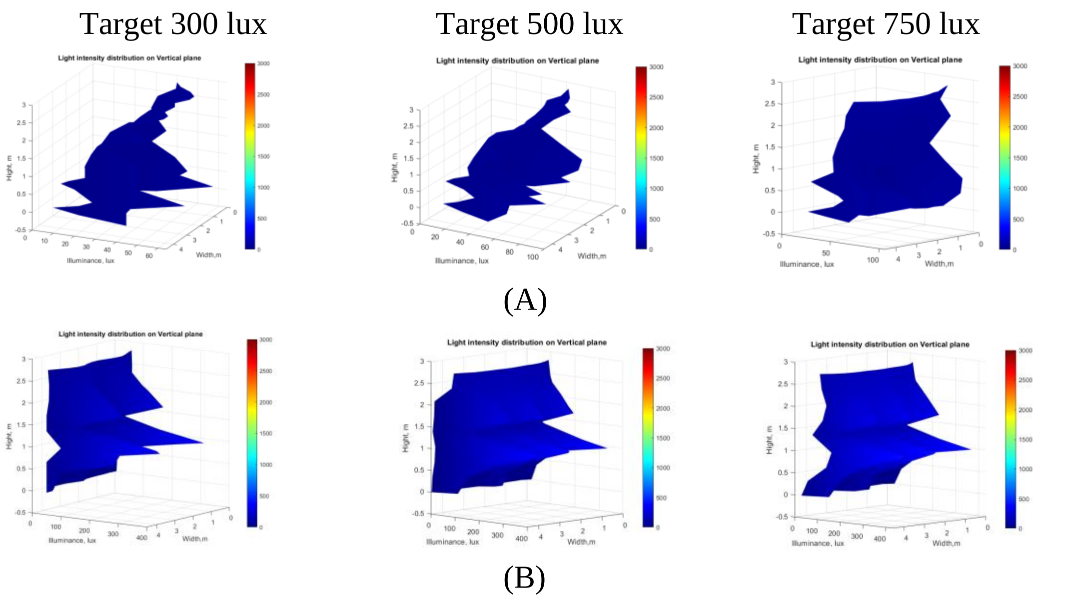


Figure A.10: LINEAR SUSPENDED D/I 20X1200 6000K %50: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

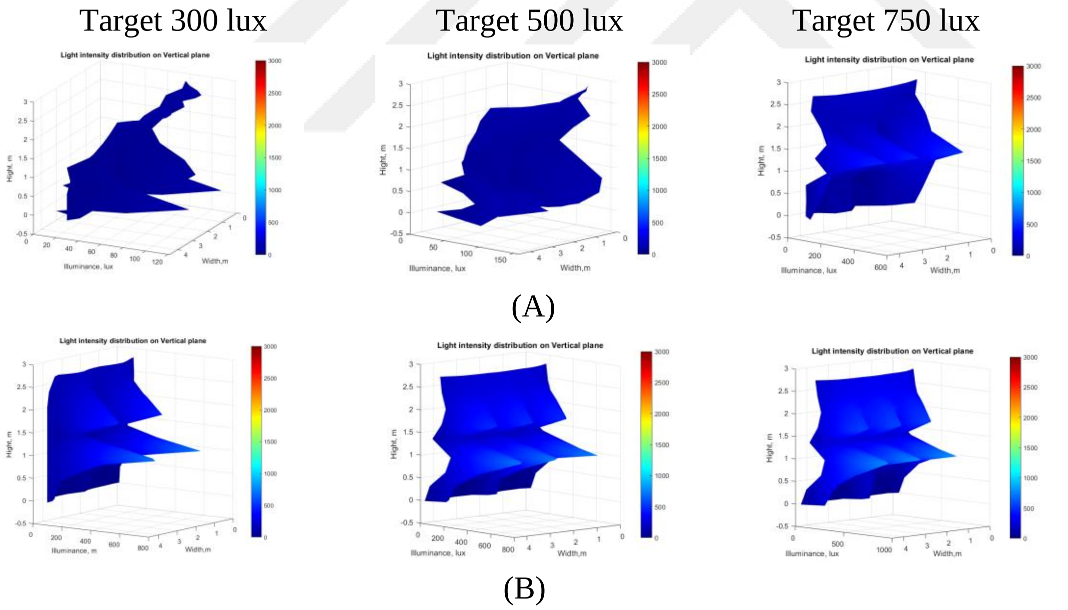
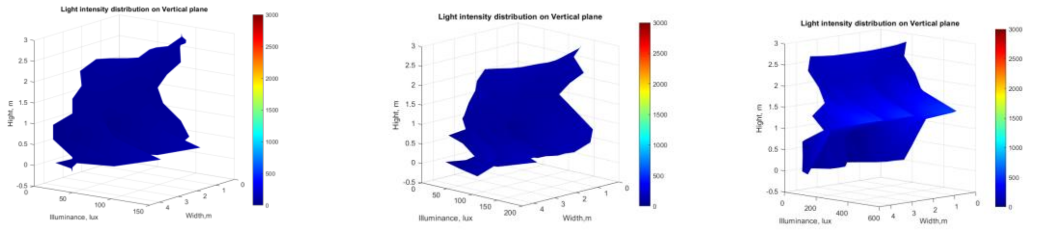
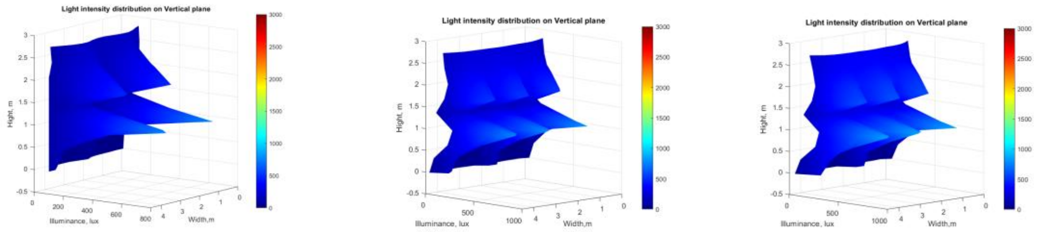


Figure A.11: LINEAR SUSPENDED D/I 20X1200 2700K %100: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux



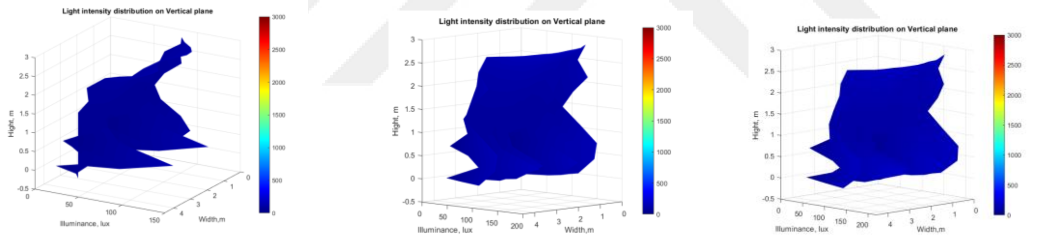
(A)



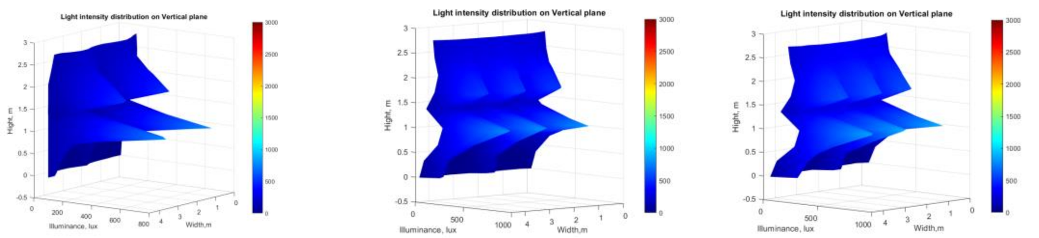
(B)

Figure A.12: LINEAR SUSPENDED D/I 20X1200 3800K %100: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux

Target 300 lux Target 500 lux Target 750 lux



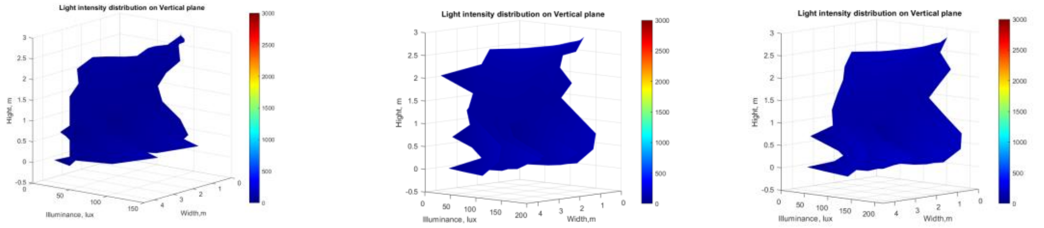
(A)



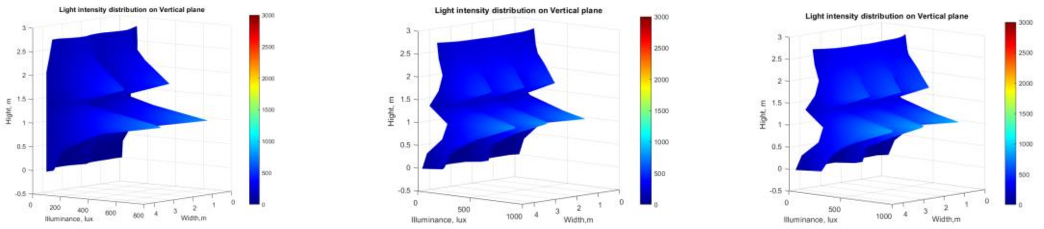
(B)

Figure A.13: LINEAR SUSPENDED D/I 20X1200 5000K %100: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux



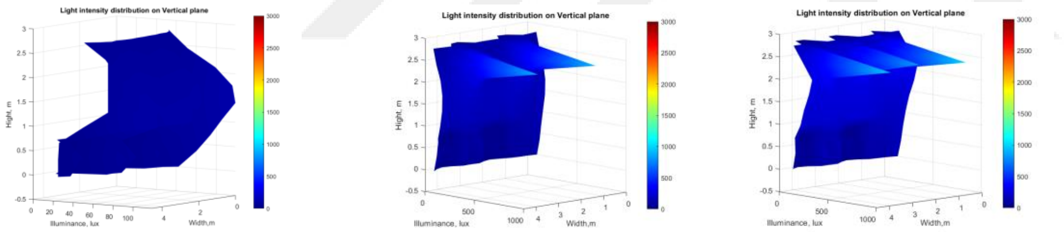
(A)



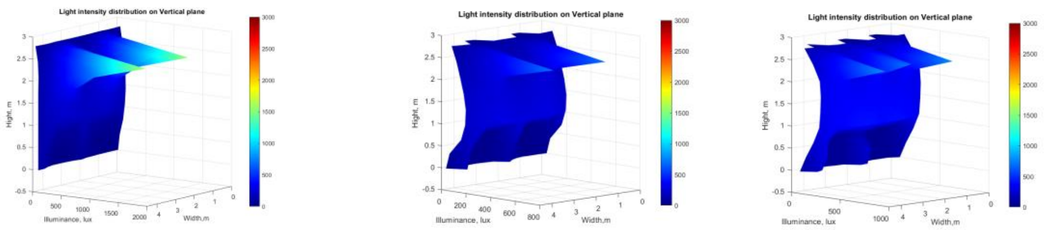
(B)

Figure A.14: LINEAR SUSPENDED D/I 20X1200 6000K %100: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

Target 300 lux Target 500 lux Target 750 lux



(A)



(B)

Figure A.15: PANEL 600: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

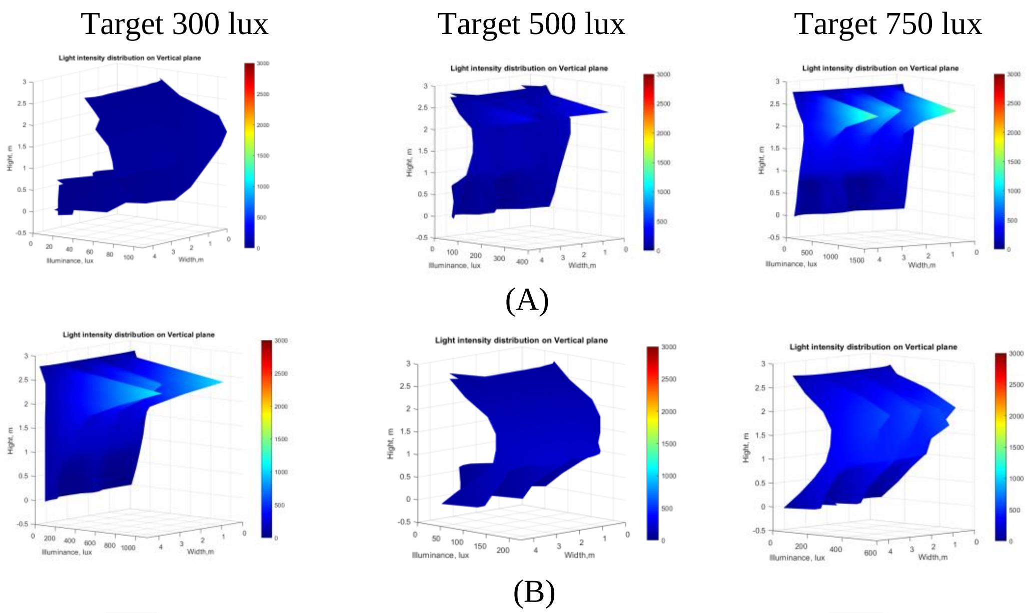


Figure A.16: ROUND RECESSED 220X220: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

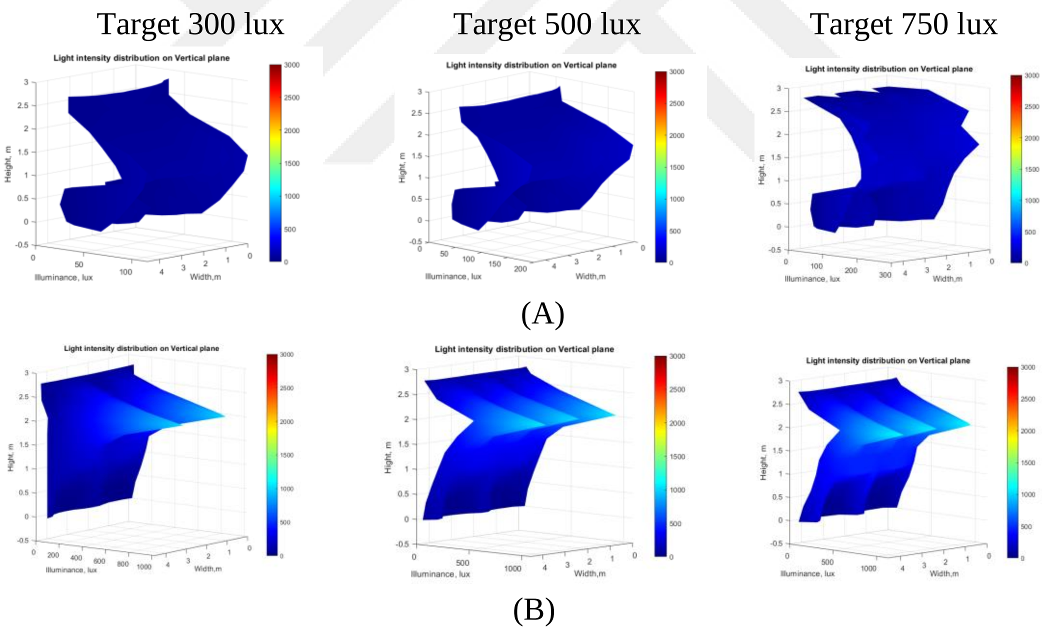
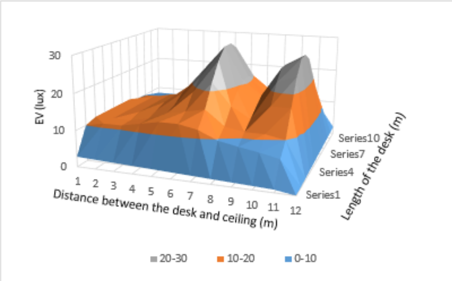
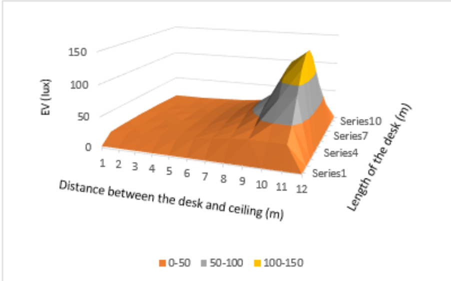


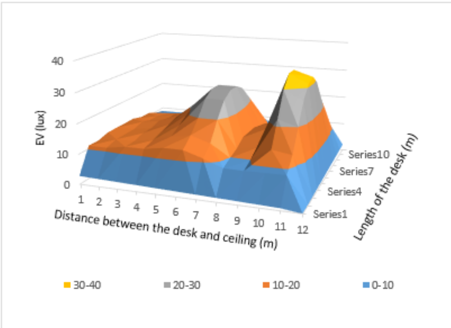
Figure A.17: LINEAR RECESSED 1200: (A) Current arrangement 3D vertical illumination at user1 and user 4 desk array, for lighting calculation with target 300 lux, 500 lux, 750 lux, (B) Revised suggested arrangement 3D vertical illumination at user1 and user 4 desk array for target 300 lux, 500 lux, 750 lux.

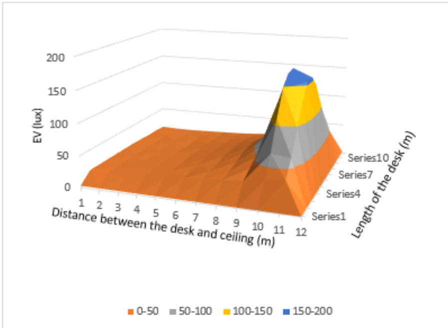
LINEAR SUSPENDED D/I %20 | LINEAR SUSPENDED %20



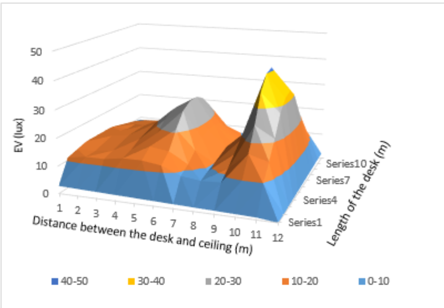


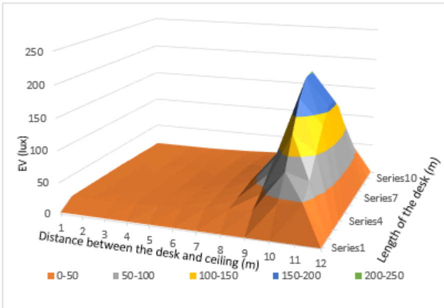
(A)



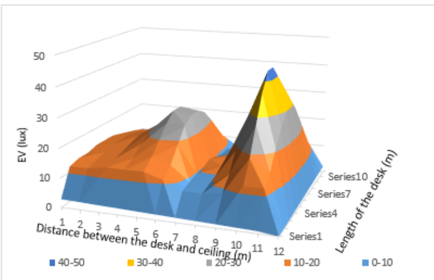


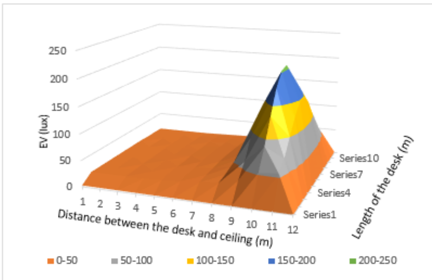
(B)





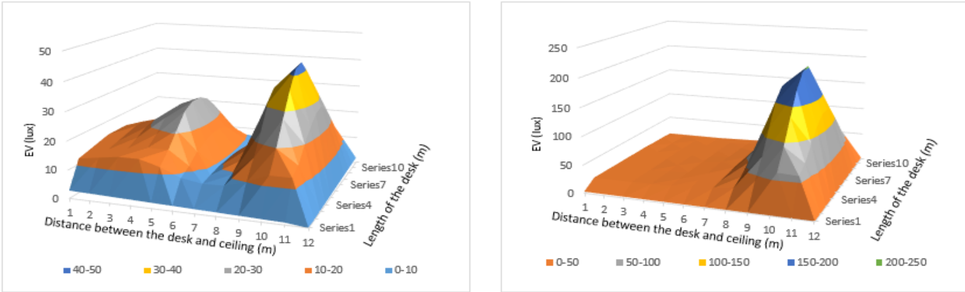
(C)



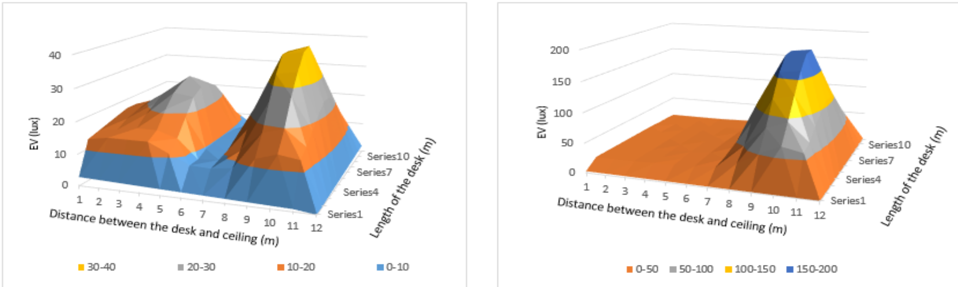


(D)

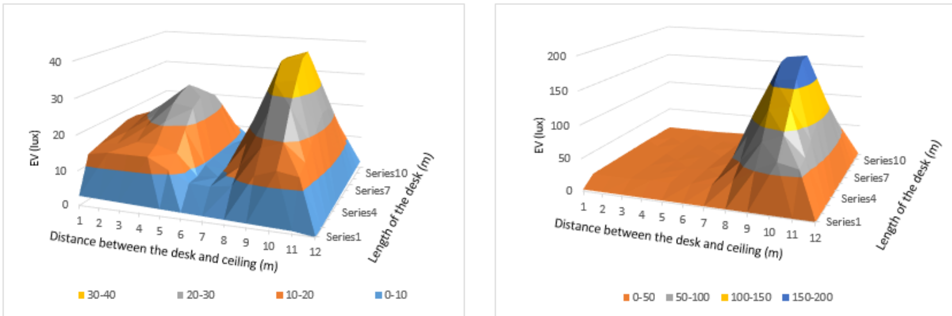
LINEAR SUSPENDED D/I %20 LINEAR SUSPENDED %20



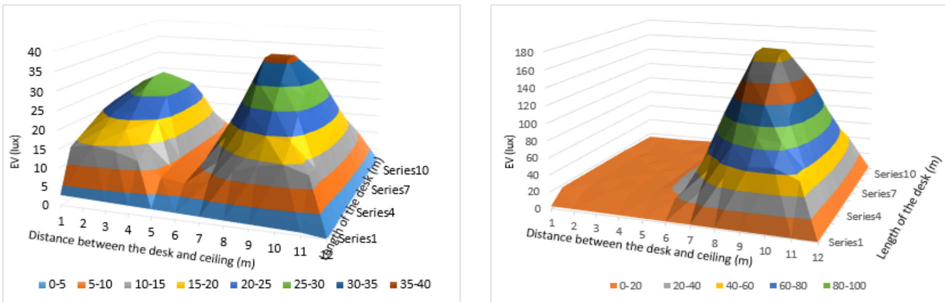
(E)



(F)



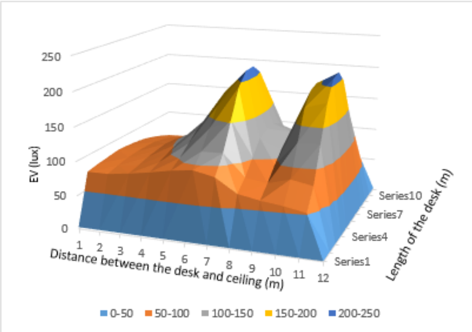
(G)

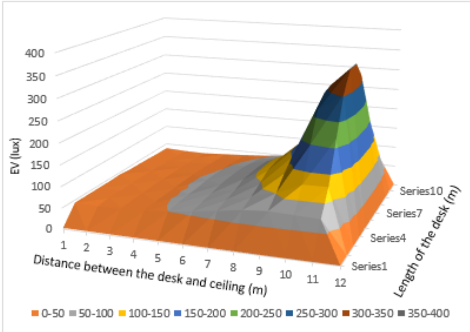


(H)

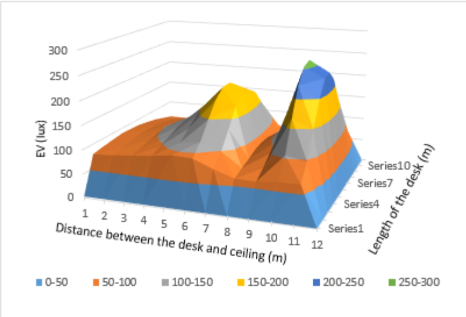
Figure A.18: Comparison of LINEAR SUSPENDED D/I %20 and LINEAR SUSPENDED 20% luminaire places at different heights: (A) 1.3m, (B) 1.4m, (C) 1.5m, (D) 1.6m, (E) 1.7m, (F) 1.8m, (G) 1.9m, (H) 2m. The X-axis represents the length of the desk (Series1-Series7), the Y-axis represents the distance between the desk and the ceiling (2 meters), and the Z-axis represents EV (lux). The curves represent the intensity of the EV at eye level in the view direction of the occupants.

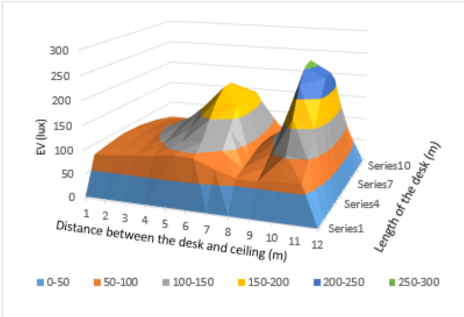
LINEAR SUSPENDED D/I %50 LINEAR SUSPENDED %50



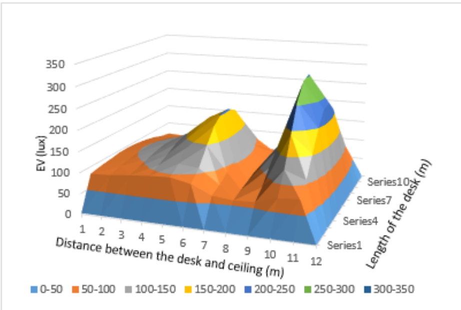


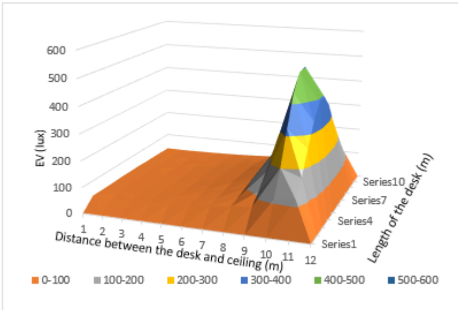
(A)



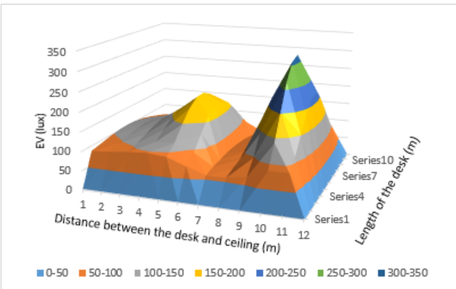


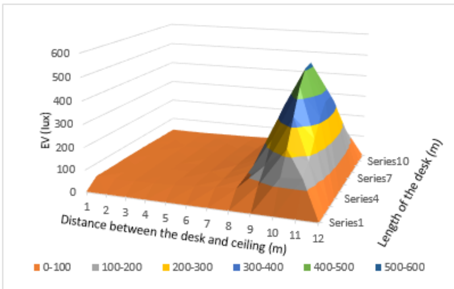
(B)





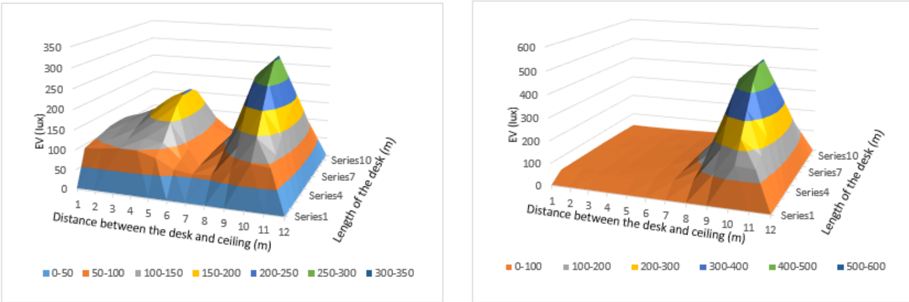
(C)



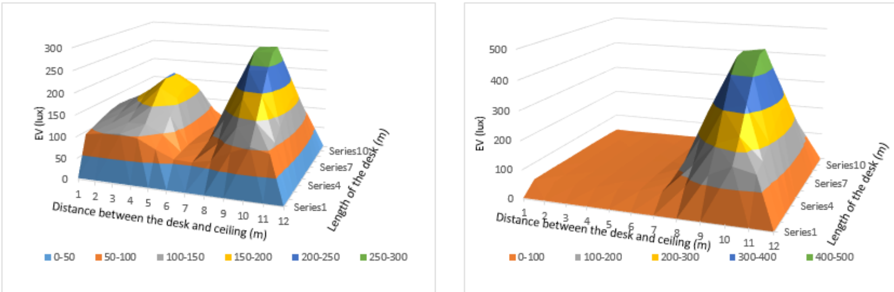


(D)

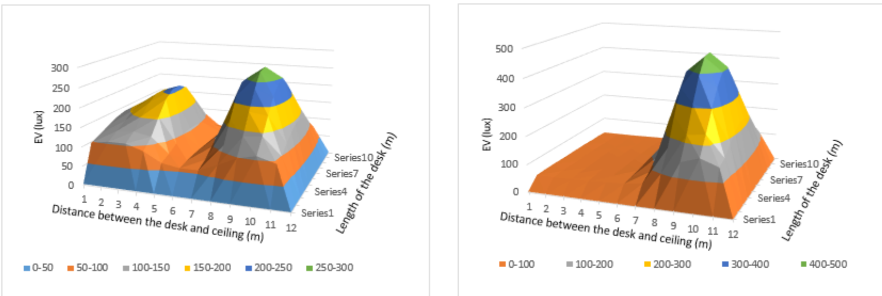
LINEAR SUSPENDED D/I %20 LINEAR SUSPENDED %20



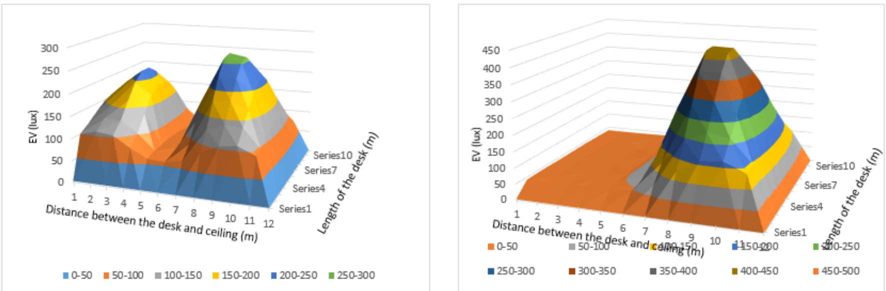
(E)



(F)



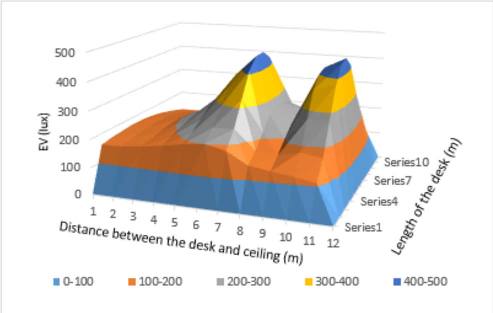
(G)

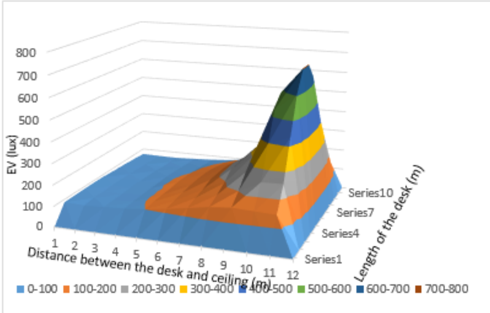


(H)

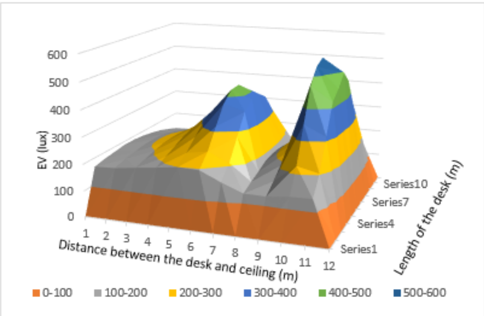
Figure A.19: Comparison of LINEAR SUSPENDED D/I %50 and LINEAR SUSPENDED 50% luminaire places at different heights: (A) 1.3m, (B) 1.4m, (C) 1.5m, (D) 1.6m, (E) 1.7m, (F) 1.8m, (G) 1.9m, (H) 2m. The X-axis represents the length of the desk (Series1-Series7), the Y-axis represents the distance between the desk and the ceiling (2 meters), and the Z-axis represents EV (lux). The curves represent the intensity of the EV at eye level in the view direction of the occupants.

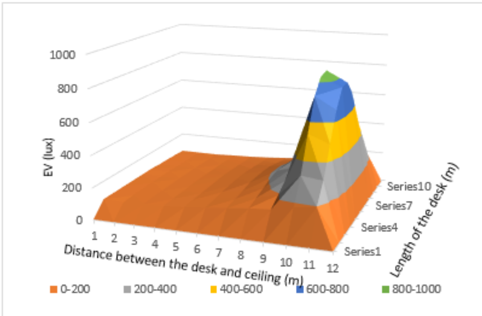
LINEAR SUSPENDED D/I %100 | LINEAR SUSPENDED %100



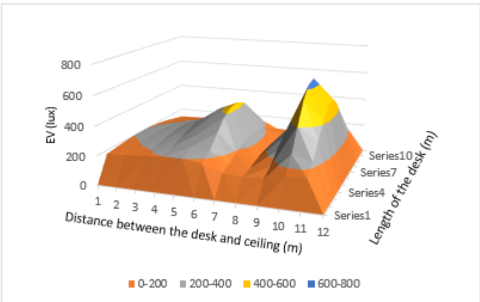


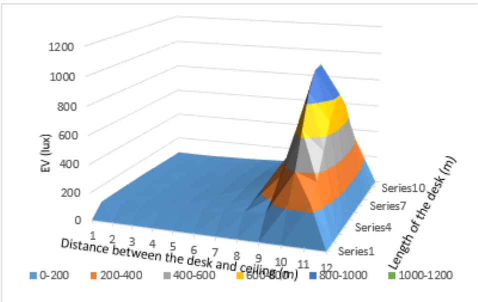
(A)



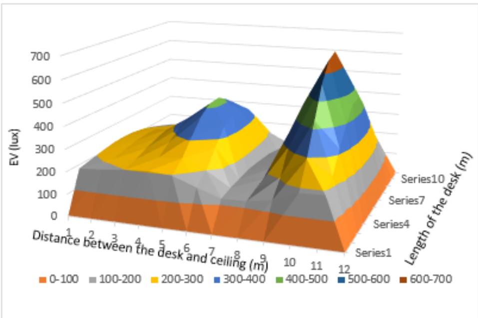


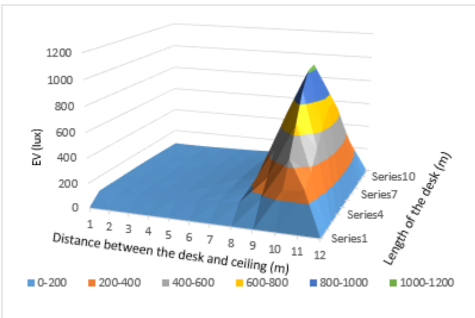
(B)





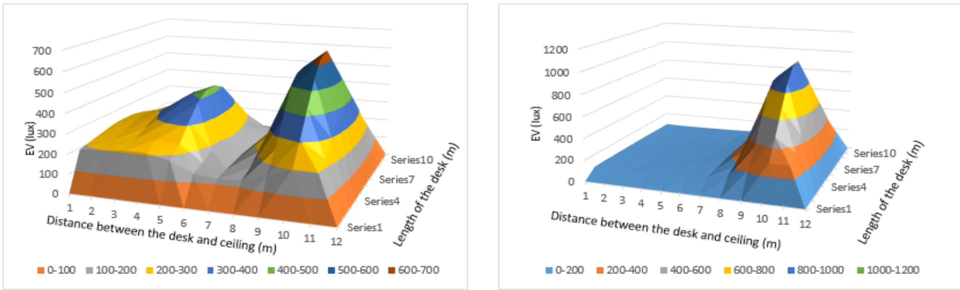
(C)



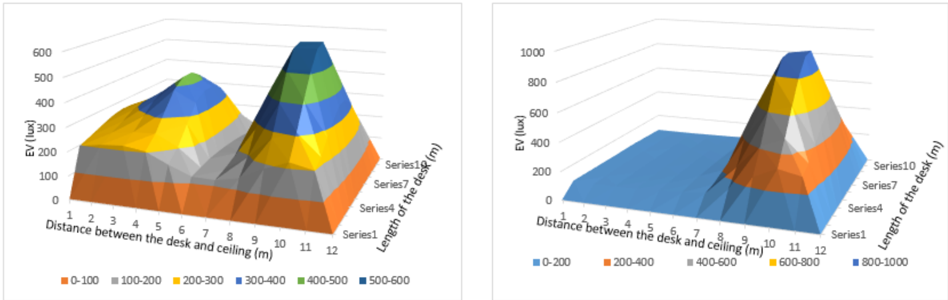


(D)

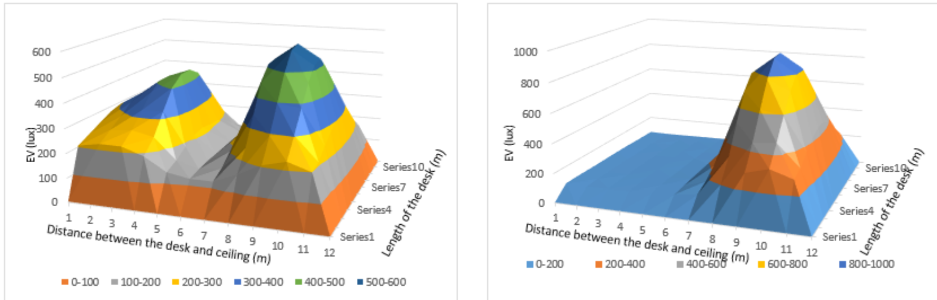
LINEAR SUSPENDED D/I %20 LINEAR SUSPENDED %20



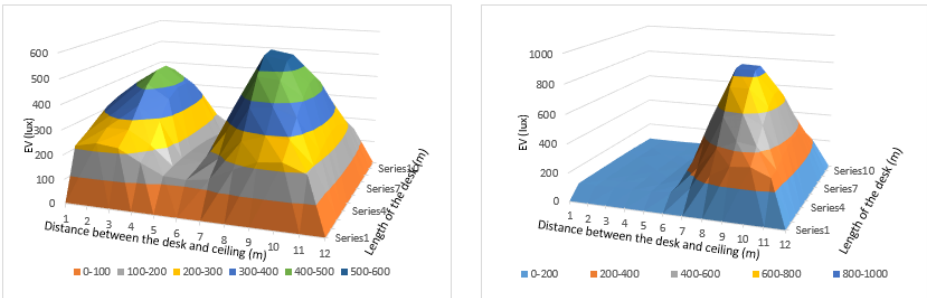
(E)



(F)



(G)



(H)

Figure A.20: Comparison of LINEAR SUSPENDED D/I %100 and LINEAR SUSPENDED 100% luminaire places at different heights: (A) 1.3m, (B) 1.4m, (C) 1.5m, (D) 1.6m, (E) 1.7m, (F) 1.8m, (G) 1.9m, (H) 2m. The X-axis represents the length of the desk (Series1-Series7), the Y-axis represents the distance between the desk and the ceiling (2 meters), and the Z-axis represents EV (lux). The curves represent the intensity of the EV at eye level in the view direction of the occupants.

Table A.3: Measured SPDs of the luminaires at laboratuary of Istanbul Technical University.

WAVELENGTH (nm)	380	385	390	395	400	405	410	415	420	425	430
SQUARE RECESSED 325X325	0.0001	0.00022	0.00019	0.0001	9.1E-05	0.00018	0.00018	0.00031	0.00054	0.00103	0.00207
LINEAR D/I SUSPENDED 20X1200 2700K %20	3.9E-05	3.2E-05	2.8E-05	2.6E-05	1.8E-05	3.1E-05	2.7E-05	3.1E-05	5.9E-05	0.00011	0.00018
LINEAR D/I SUSPENDED 20X1200 2700K %50	0.00012	0.00019	0.00019	8.84E-05	0.00012	0.00018	0.00018	0.00026	0.00039	0.00076	0.00142
LINEAR D/I SUSPENDED 20X1200 2700K %100	0.00041	0.00032	0.0003	0.00036	0.00018	0.00036	0.00036	0.00056	0.00095	0.00191	0.00319
LINEAR D/I SUSPENDED 20X1200 3800K %20	3.57E-05	3.73E-05	3.11E-05	1.99E-05	2.87E-05	3.37E-05	3.53E-05	4.98E-05	7.99E-05	0.00018	0.00034
LINEAR D/I SUSPENDED 20X1200 3800K ~3900K %50	0.00027	0.00029	0.0003	0.00019	0.0002	0.00022	0.00026	0.0004	0.00071	0.00139	0.00271
LINEAR D/I SUSPENDED 20X1200	0.00048	0.00037	0.00064	0.00046	0.00047	0.00044	0.00058	0.0009	0.00159	0.00336	0.00653
LINEAR D/I SUSPENDED 20X1200	4.31E-05	3.05E-05	3.48E-05	3.32E-05	3.72E-05	3.87E-05	4.19E-05	6.94E-05	0.00011	0.00023	0.00046
LINEAR D/I SUSPENDED 20X1200 5000K %50	0.00026	0.00034	0.00032	0.00016	0.00019	0.00026	0.00031	0.00055	0.00095	0.00192	0.00387
LINEAR D/I SUSPENDED 20X1200 5000K %100	0.00053	0.0004	0.00059	0.00053	0.00043	0.00057	0.00071	0.00112	0.00223	0.00468	0.00931
LINEAR D/I SUSPENDED 20X1200 6000K %20	4.20E-05	4.40E-05	3.60E-05	3.73E-05	3.76E-05	5.16E-05	5.17E-05	7.18E-05	0.00013	0.00027	0.00054
LINEAR SUSPENDED 20X1200 6000K %50	0.0003	0.0003	0.0003	0.0003	0.0002	0.0003	0.0004	0.0006	0.0011	0.0023	0.0045
LINEAR D/I SUSPENDED 20X1200 6000K %100	0.00065	0.00043	0.00056	0.00061	0.00049	0.00071	0.00083	0.00147	0.00263	0.00568	0.01117
PANEL 600	4E-04	3E-04	3E-04	3E-04	3E-04	4E-04	6E-04	0.001	0.002	0.004	0.007
ROUND RECESSED 220X220	0.00024	0.0003	0.00021	0.00021	0.00023	0.00037	0.00074	0.00153	0.00306	0.00593	0.01039
LINEAR RECESSED 1200	0.0005	0.0004	0.0003	0.0004	0.0003	0.0004	0.0006	0.0011	0.002	0.0039	0.0073

Table A.3 (continued): Measured SPDs of the luminaires at laboratuary of Istanbul Technical University.

435	0.00417	0.00031	0.00257	0.00575	0.00066	0.00543	0.0127	0.00094	0.00776	0.01794	0.00109	0.0091	0.02169	0.012	0.0179	0.0131
440	0.00785	0.00054	0.00423	0.00946	0.00123	0.00991	0.02261	0.00175	0.01404	0.03242	0.00208	0.0168	0.03857	0.02	0.02632	0.0222
445	0.01555	0.00095	0.00707	0.01526	0.00238	0.01917	0.04248	0.00341	0.02707	0.06072	0.00409	0.0328	0.07185	0.029	0.02698	0.036
450	0.02674	0.00143	0.0102	0.02139	0.00433	0.03297	0.07054	0.00627	0.04664	0.09829	0.00757	0.0556	0.11278	0.028	0.01801	0.046
455	0.02563	0.00158	0.01105	0.02278	0.0047	0.03383	0.07005	0.00687	0.04725	0.09522	0.00812	0.0544	0.10755	0.018	0.01237	0.0416
460	0.01549	0.00165	0.01046	0.02055	0.0032	0.0224	0.04637	0.00441	0.02985	0.06097	0.00502	0.0331	0.068	0.013	0.00918	0.0293
465	0.01265	0.00139	0.00853	0.0167	0.00246	0.01729	0.03588	0.00328	0.0227	0.04674	0.00372	0.0254	0.05196	0.01	0.00647	0.0228
470	0.01055	0.00112	0.00718	0.01431	0.00203	0.0142	0.02923	0.0027	0.01837	0.0372	0.00308	0.0204	0.04106	0.007	0.00502	0.0186
475	0.00778	0.00105	0.00662	0.01307	0.00157	0.01089	0.02268	0.00198	0.01353	0.02763	0.00219	0.0146	0.03008	0.006	0.00483	0.0153
480	0.00756	0.00098	0.00619	0.01233	0.0014	0.00982	0.02055	0.00173	0.01206	0.02491	0.00191	0.0132	0.02707	0.007	0.00536	0.015
485	0.00856	0.00098	0.00643	0.01304	0.00143	0.01027	0.02153	0.00179	0.01262	0.02605	0.00199	0.0138	0.02849	0.008	0.0066	0.0168
490	0.00959	0.00109	0.0073	0.01483	0.00155	0.0112	0.02357	0.00191	0.01352	0.0281	0.00213	0.0148	0.03071	0.01	0.00837	0.0194
495	0.0111	0.00126	0.00852	0.01737	0.00175	0.01265	0.02671	0.00212	0.01514	0.03171	0.00236	0.0166	0.03429	0.013	0.01058	0.0228
500	0.01256	0.0014	0.00956	0.01963	0.00194	0.01411	0.02978	0.00234	0.01675	0.03498	0.0026	0.0184	0.03794	0.017	0.01256	0.0259
505	0.01374	0.00155	0.01054	0.0218	0.00209	0.0154	0.03237	0.00251	0.01811	0.03794	0.0028	0.0198	0.04085	0.02	0.01431	0.0286

Table A.3 (continued): Measured SPDs of the luminaires at laboratuary of Istanbul Technical University.

510	0.01453	0.00167	0.01141	0.02357	0.00223	0.0163	0.03434	0.00265	0.01902	0.03999	0.00293	0.0208	0.04272	0.023	0.01576	0.0306
515	0.01501	0.00176	0.01207	0.02492	0.00231	0.01691	0.03581	0.00274	0.01967	0.04122	0.00302	0.0214	0.04405	0.026	0.01698	0.0321
520	0.01537	0.00185	0.01275	0.02631	0.00239	0.01748	0.037	0.00281	0.02024	0.04259	0.0031	0.022	0.04527	0.028	0.01782	0.0333
525	0.01561	0.00193	0.01325	0.02735	0.00244	0.01787	0.03771	0.00284	0.02038	0.04294	0.00314	0.0223	0.04572	0.029	0.01847	0.034
530	0.01589	0.00201	0.01392	0.02874	0.00251	0.0183	0.03887	0.0029	0.0209	0.04412	0.00318	0.0227	0.04645	0.031	0.01914	0.035
535	0.01624	0.0021	0.01454	0.03004	0.00258	0.01876	0.03986	0.00294	0.02123	0.04486	0.00322	0.0229	0.04715	0.033	0.01958	0.036
540	0.01671	0.00223	0.01539	0.03187	0.00267	0.01942	0.04111	0.00302	0.02184	0.04583	0.0033	0.0235	0.04813	0.034	0.02022	0.0373
545	0.01712	0.00236	0.01622	0.03357	0.00275	0.02002	0.04241	0.00308	0.02223	0.0468	0.00335	0.0237	0.04876	0.036	0.02074	0.0386
550	0.01767	0.0025	0.01725	0.03565	0.00284	0.02067	0.04367	0.00314	0.02262	0.04758	0.00338	0.0239	0.04924	0.038	0.02129	0.04
555	0.01836	0.00268	0.01844	0.03838	0.00295	0.02132	0.04535	0.00321	0.02313	0.04862	0.00343	0.0244	0.05001	0.04	0.02184	0.0414
560	0.01905	0.00287	0.01984	0.04102	0.00305	0.02218	0.04695	0.00326	0.02345	0.04957	0.00347	0.0244	0.05037	0.042	0.02253	0.0433
565	0.01977	0.00309	0.02131	0.04428	0.00317	0.02294	0.04857	0.00332	0.0239	0.05033	0.0035	0.0246	0.05073	0.045	0.02308	0.0449
570	0.02056	0.00334	0.02304	0.04764	0.00331	0.02382	0.05046	0.00339	0.0243	0.05111	0.00352	0.0248	0.05093	0.047	0.02368	0.0467
575	0.02125	0.00362	0.02491	0.05148	0.00344	0.02491	0.05252	0.00345	0.02471	0.05236	0.00354	0.0247	0.05126	0.05	0.02433	0.0485
580	0.02187	0.00389	0.02674	0.05526	0.00357	0.02569	0.05437	0.0035	0.02505	0.05283	0.00353	0.0247	0.051	0.052	0.02469	0.05

Table A.3 (continued): Measured SPDs of the luminaires at laboratuary of Istanbul Technical University.

585	0.02252	0.00414	0.02854	0.05853	0.00368	0.02656	0.05604	0.00352	0.02526	0.05314	0.00352	0.0246	0.05061	0.055	0.02518	0.0512
590	0.02274	0.00437	0.03002	0.0619	0.00381	0.02719	0.0576	0.00355	0.02533	0.0533	0.00346	0.0242	0.05003	0.056	0.02527	0.052
595	0.02289	0.00456	0.03135	0.06469	0.00389	0.02769	0.05862	0.00355	0.02521	0.05305	0.00342	0.0238	0.04921	0.058	0.02539	0.0524
600	0.0228	0.00471	0.03236	0.06658	0.00395	0.02814	0.05942	0.00357	0.0251	0.05284	0.00339	0.0232	0.04816	0.059	0.02537	0.0522
605	0.02242	0.0048	0.03282	0.06732	0.00393	0.02802	0.05895	0.00347	0.02451	0.05169	0.00325	0.0225	0.04639	0.058	0.02513	0.0512
610	0.0219	0.00484	0.03299	0.06764	0.00391	0.02781	0.05832	0.00337	0.02391	0.05015	0.00312	0.0216	0.04482	0.058	0.0247	0.05
615	0.02103	0.00476	0.03258	0.06665	0.00382	0.02704	0.05674	0.00325	0.02291	0.04844	0.00297	0.0206	0.04243	0.058	0.02417	0.048
620	0.01993	0.00466	0.03173	0.06483	0.00367	0.02599	0.05458	0.00311	0.02176	0.0457	0.00282	0.0194	0.04011	0.057	0.02334	0.0454
625	0.01874	0.00447	0.0304	0.06213	0.00351	0.0246	0.05208	0.00291	0.02041	0.04316	0.00264	0.018	0.03737	0.055	0.02219	0.0424
630	0.01728	0.00426	0.02877	0.05899	0.00329	0.02311	0.04854	0.00271	0.01902	0.04001	0.00244	0.0168	0.03441	0.052	0.02109	0.0393
635	0.01586	0.00398	0.02696	0.05517	0.00306	0.02153	0.04502	0.00249	0.01755	0.03686	0.00224	0.0154	0.03166	0.049	0.01996	0.0357
640	0.01437	0.00366	0.02495	0.05088	0.0028	0.01972	0.04133	0.00228	0.016	0.03347	0.00203	0.014	0.02862	0.045	0.01848	0.0323
645	0.01294	0.00333	0.02269	0.0464	0.00254	0.01789	0.03776	0.00206	0.01444	0.0305	0.00184	0.0125	0.02579	0.041	0.01712	0.0291
650	0.01158	0.00304	0.02062	0.04215	0.0023	0.01618	0.03398	0.00185	0.013	0.02742	0.00163	0.0112	0.02308	0.038	0.01588	0.026
655	0.01033	0.00275	0.01863	0.03794	0.00207	0.01461	0.0305	0.00166	0.01163	0.02446	0.00146	0.01	0.02058	0.035	0.01448	0.023

Table A.3 (continued): Measured SPDs of the luminaires at laboratuary of Istanbul Technical University.

660	0.00901	0.00244	0.01654	0.03379	0.00183	0.01296	0.02704	0.00146	0.0103	0.02157	0.00128	0.0088	0.01815	0.031	0.01309	0.02
665	0.00786	0.00216	0.01467	0.02998	0.00162	0.01141	0.02386	0.00129	0.00905	0.01901	0.00113	0.0076	0.01583	0.028	0.01177	0.0175
670	0.00678	0.00191	0.01283	0.02636	0.00141	0.00998	0.02083	0.00112	0.00783	0.01657	0.00097	0.0067	0.01375	0.025	0.01051	0.0151
675	0.00589	0.00168	0.01139	0.02343	0.00124	0.0087	0.0184	0.00098	0.00687	0.01447	0.00084	0.0058	0.01203	0.022	0.00947	0.013
680	0.0051	0.00146	0.00986	0.02038	0.00109	0.00759	0.01611	0.00085	0.00592	0.01255	0.00073	0.0051	0.0103	0.019	0.00844	0.0114
685	0.00443	0.00131	0.00867	0.01769	0.001	0.00664	0.01391	0.00078	0.00522	0.01092	0.00067	0.0044	0.00909	0.017	0.00739	0.0097
690	0.00377	0.0011	0.00746	0.01522	0.00081	0.00573	0.01189	0.00063	0.0045	0.00932	0.00054	0.0037	0.00781	0.015	0.00647	0.0084
695	0.00322	0.00096	0.00637	0.01335	0.0007	0.00493	0.01034	0.00054	0.0039	0.00798	0.00048	0.0033	0.00663	0.013	0.00571	0.0071
700	0.00272	0.00082	0.00555	0.01143	0.00059	0.00425	0.00877	0.00046	0.00325	0.00695	0.0004	0.0028	0.00572	0.011	0.00498	0.006
705	0.0024	0.00071	0.00484	0.00994	0.00051	0.00365	0.00774	0.00041	0.00291	0.00625	0.00035	0.0025	0.00515	0.009	0.00442	0.0054
710	0.00198	0.00059	0.00408	0.00826	0.00044	0.00308	0.00635	0.00033	0.0024	0.00504	0.0003	0.0021	0.00425	0.007	0.00378	0.0044
715	0.00163	0.00051	0.00344	0.0071	0.00037	0.00259	0.00546	0.00029	0.00203	0.00434	0.00025	0.0017	0.00344	0.006	0.00327	0.0037
720	0.00145	0.00044	0.00297	0.00614	0.00032	0.00224	0.00481	0.00025	0.00178	0.00368	0.00021	0.0015	0.0031	0.006	0.00281	0.0033
725	0.00129	0.00038	0.00258	0.00531	0.00029	0.00204	0.00411	0.00022	0.00157	0.00326	0.0002	0.0015	0.00276	0.005	0.00252	0.0028
730	0.00101	0.00031	0.00216	0.0043	0.00023	0.00159	0.00342	0.00019	0.00132	0.00271	0.00015	0.0011	0.00217	0.004	0.00212	0.0023

Table A.4: Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

L1 3800K	
Derived Data	
Radiant Flux (Watts)	8.83E+00
Luminous Flux (lumens)	2.94E+03
Scotopic Luminous Flux (lm')	4.80E+03
Chromaticity x coord	0.3919
Chromaticity y coord	0.3902
Chromaticity u coord	0.2273
Chromaticity v coord	0.3394
Delta uv	0.0027
Chromaticity u' coord	0.2273
Chromaticity v' coord	0.5091
Peak Wavelength (nm)	593.8
Center Wavelength (nm)	575.1
Centroid Wavelength (nm)	567.3
Dominant Wavelength (nm)	578.4
Full Width Half Max Bandwidth (nm)	148.9
Excitation Purity (%)	34.7
Correlated Color Temperature (deg. K)	3802
SDCM	57.2 F 6500
Correlation	0.0054
Correlation Coeficient	0.00298216
Color Rendering Index Average (RA)	82.4925528
Color Rendering Index (R1)	80.1
Color Rendering Index (R2)	89.2

L2 2700K	
Derived Data	
Radiant Flux (Watts)	9.63E+00
Luminous Flux (lumens)	3.07E+03
Scotopic Luminous Flux (lm')	3.82E+03
Chromaticity x coord	0.4593
Chromaticity y coord	0.4104
Chromaticity u coord	0.2623
Chromaticity v coord	0.3515
Delta uv	0.0004
Chromaticity u' coord	0.2623
Chromaticity v' coord	0.5272
Peak Wavelength (nm)	609.2
Center Wavelength (nm)	602.7
Centroid Wavelength (nm)	589.7
Dominant Wavelength (nm)	584.2
Full Width Half Max Bandwidth (nm)	114.5
Excitation Purity (%)	61.1
Correlated Color Temperature (deg. K)	2703
SDCM	110.6 F 6500
Correlation	0.0054
Correlation Coeficient	0.000218306
Color Rendering Index Average (RA)	83.11531668
Color Rendering Index (R1)	82.2
Color Rendering Index (R2)	93.3

L2 3800K	
Derived Data	
Radiant Flux (Watts)	1.07E+01
Luminous Flux (lumens)	3.30E+03
Scotopic Luminous Flux (lm')	5.72E+03
Chromaticity x coord	0.3836
Chromaticity y coord	0.3672
Chromaticity u coord	0.2311
Chromaticity v coord	0.3319
Delta uv	0.0056
Chromaticity u' coord	0.2311
Chromaticity v' coord	0.4978
Peak Wavelength (nm)	452.6
Center Wavelength (nm)	453.9
Centroid Wavelength (nm)	568.1
Dominant Wavelength (nm)	583
Full Width Half Max Bandwidth (nm)	19.4
Excitation Purity (%)	25.3
Correlated Color Temperature (deg. K)	3835
SDCM	54.7 F 6500
Correlation	0.0054
Correlation Coeficient	0.00543029
Color Rendering Index Average (RA)	88.3347324
Color Rendering Index (R1)	89
Color Rendering Index (R2)	95.8

L2 6000K	
Derived Data	
Radiant Flux (Watts)	1.11E+01
Luminous Flux (lumens)	3.36E+03
Scotopic Luminous Flux (lm')	7.43E+03
Chromaticity x coord	0.3216
Chromaticity y coord	0.3319
Chromaticity u coord	0.203
Chromaticity v coord	0.3141
Delta uv	0.0002
Chromaticity u' coord	0.203
Chromaticity v' coord	0.4712
Peak Wavelength (nm)	451.9
Center Wavelength (nm)	452.7
Centroid Wavelength (nm)	544.6
Dominant Wavelength (nm)	490.1
Full Width Half Max Bandwidth (nm)	18.8
Excitation Purity (%)	4
Correlated Color Temperature (deg. K)	6018
SDCM	10.5 F 6500
Correlation	0.0054
Correlation Coeficient	0.00296487
Color Rendering Index Average (RA)	86.5471139
Color Rendering Index (R1)	85.9
Color Rendering Index (R2)	91.8

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

Color Rendering Index (R3)	96.4	Color Rendering Index (R3)	93.8	Color Rendering Index (R3)	95.8	Color Rendering Index (R3)	93.7
Color Rendering Index (R4)	81.2	Color Rendering Index (R4)	80.7	Color Rendering Index (R4)	87.1	Color Rendering Index (R4)	86.1
Color Rendering Index (R5)	80.6	Color Rendering Index (R5)	82.8	Color Rendering Index (R5)	89.2	Color Rendering Index (R5)	86
Color Rendering Index (R6)	86.1	Color Rendering Index (R6)	93.3	Color Rendering Index (R6)	91.9	Color Rendering Index (R6)	86.1
Color Rendering Index (R7)	85.2	Color Rendering Index (R7)	81.1	Color Rendering Index (R7)	86.3	Color Rendering Index (R7)	88.9
Color Rendering Index (R8)	61.2	Color Rendering Index (R8)	57.9	Color Rendering Index (R8)	71.6	Color Rendering Index (R8)	73.8
Color Rendering Index (R9)	1.6	Color Rendering Index (R9)	10.2	Color Rendering Index (R9)	33.5	Color Rendering Index (R9)	24.4
Color Rendering Index (R10)	75.5	Color Rendering Index (R10)	85.3	Color Rendering Index (R10)	89.3	Color Rendering Index (R10)	79.2
Color Rendering Index (R11)	80.6	Color Rendering Index (R11)	80.8	Color Rendering Index (R11)	87.5	Color Rendering Index (R11)	86.1
Color Rendering Index (R12)	64.8	Color Rendering Index (R12)	79.3	Color Rendering Index (R12)	72.1	Color Rendering Index (R12)	62.4
Color Rendering Index (R13)	82.3	Color Rendering Index (R13)	84.9	Color Rendering Index (R13)	91.4	Color Rendering Index (R13)	88.1
Color Rendering Index (R14)	98.3	Color Rendering Index (R14)	97.3	Color Rendering Index (R14)	98.8	Color Rendering Index (R14)	97
Spectral Data		Spectral Data		Spectral Data		Spectral Data	
Wavelength (nm)	Scan1	Wavelength (nm)	Scan1	Wavelength (nm)	Scan1	Wavelength (nm	Scan1
350	0.00055923	350	0.000429535	350	0.00073428	350	0.00070716
351	0.00065122	351	0.000535604	351	0.00071739	351	0.00073468
352	0.00049548	352	0.000743544	352	0.00066792	352	0.00080832
353	0.00075937	353	0.000173254	353	0.00101534	353	0.0004328
354	0.00045668	354	0.000715288	354	0.0003617	354	0.00070381
355	0.00069203	355	0.000314604	355	0.00088113	355	0.00063577
356	0.00068526	356	0.000305778	356	0.00093171	356	0.0005935
357	0.00044128	357	0.000592442	357	0.00051869	357	0.00087071
358	0.00057747	358	0.000543447	358	0.00071105	358	0.00081831
359	0.00064221	359	0.0003402	359	0.00078952	359	0.00068041

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

360	0.00063745	360	0.000564277	360	0.00075232	360	0.00056279
361	0.00041759	361	0.000671756	361	0.0005482	361	0.00100102
362	0.0005403	362	0.000483875	362	0.00059677	362	0.00071902
363	0.00043809	363	0.00045813	363	0.00063546	363	0.00073522
364	0.0007256	364	0.000781208	364	0.00078017	364	0.00104431
365	0.00047609	365	0.000500125	365	0.0005795	365	0.00075739
366	0.00052275	366	0.000504898	366	0.00073339	366	0.00090749
367	0.00035434	367	0.000487804	367	0.00035233	367	0.00084203
368	0.00076541	368	0.000524452	368	0.00083195	368	0.0006905
369	0.00061678	369	0.000485232	369	0.00065638	369	0.00064603
370	0.00047005	370	0.000501703	370	0.00055147	370	0.000755
371	0.00056219	371	0.000664806	371	0.00072343	371	0.00064605
372	0.00038341	372	0.00055968	372	0.00055477	372	0.00092373
373	0.00047996	373	0.000263847	373	0.00073102	373	0.00050999
374	0.00065419	374	0.000158371	374	0.0007572	374	0.00043643
375	0.00048879	375	0.000299487	375	0.00065705	375	0.00039263
376	0.00052545	376	0.000306324	376	0.00067071	376	0.00061071
377	0.00063215	377	0.000228095	377	0.000827	377	0.00048276
378	0.00038788	378	0.000143255	378	0.00064882	378	0.00025729
379	0.00062313	379	0.000481798	379	0.00064421	379	0.00076988
380	0.00046894	380	0.000410041	380	0.00057895	380	0.0006479
381	0.00043606	381	0.0004366	381	0.00067745	381	0.00064316
382	0.00030159	382	0.000434177	382	0.00058944	382	0.00067583
383	0.00059711	383	0.000445063	383	0.00060438	383	0.0006466
384	0.00024857	384	0.000534713	384	0.00046844	384	0.00078494
385	0.00049608	385	0.00031845	385	0.00059113	385	0.00042949
386	0.00047162	386	0.000498064	386	0.00058843	386	0.0007272
387	0.00045026	387	0.000238948	387	0.00071037	387	0.0005845
388	0.00043367	388	0.00017821	388	0.00067593	388	0.00054236
389	0.00052819	389	0.000648121	389	0.00056918	389	0.00084965
390	0.00052537	390	0.000297154	390	0.00062282	390	0.00055626
391	0.00054935	391	0.000594859	391	0.00078457	391	0.00071488
392	0.0005629	392	0.000473651	392	0.00052262	392	0.00057052
393	0.00040756	393	0.000292744	393	0.00056659	393	0.00053881
394	0.00048506	394	0.000496853	394	0.00068817	394	0.0006156
395	0.00051269	395	0.0003598	395	0.00069271	395	0.00061313
396	0.00049832	396	0.000554056	396	0.00062112	396	0.000772
397	0.00048218	397	0.000280139	397	0.00064296	397	0.00052209
398	0.0005398	398	0.000474736	398	0.00059639	398	0.00059296
399	0.00057045	399	0.000408193	399	0.00058899	399	0.0006012
400	0.00038604	400	0.000181648	400	0.00047859	400	0.00048856

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

401	0.00039173	401	0.000391466	401	0.00053403	401	0.00063571
402	0.00039973	402	0.000373404	402	0.00056783	402	0.00067276
403	0.00040851	403	0.000349608	403	0.00046658	403	0.00067035
404	0.00045367	404	0.000355784	404	0.00051584	404	0.00050802
405	0.00047226	405	0.000356849	405	0.00060245	405	0.00071053
406	0.00056574	406	0.00048061	406	0.00063916	406	0.00072869
407	0.00053062	407	0.000375209	407	0.00070798	407	0.0007224
408	0.00060296	408	0.000226325	408	0.00063916	408	0.00067537
409	0.00069106	409	0.000350468	409	0.00072029	409	0.0007714
410	0.00061226	410	0.00035913	410	0.0006457	410	0.0008314
411	0.00071076	411	0.000437306	411	0.00062924	411	0.00095216
412	0.00072033	412	0.000425061	412	0.00060206	412	0.00093905
413	0.00083073	413	0.000537242	413	0.00071741	413	0.00113513
414	0.00097661	414	0.000533471	414	0.00088455	414	0.00135961
415	0.00098599	415	0.00056244	415	0.00099549	415	0.00147095
416	0.00110886	416	0.000722535	416	0.00097932	416	0.00161286
417	0.00126871	417	0.000759494	417	0.00108742	417	0.00184903
418	0.0014886	418	0.000743442	418	0.00133467	418	0.00209444
419	0.00172553	419	0.001071912	419	0.00150944	419	0.00247304
420	0.00192765	420	0.00095446	420	0.00172087	420	0.00263041
421	0.00221109	421	0.00113988	421	0.00179456	421	0.00316623
422	0.0024341	422	0.001261004	422	0.00207125	422	0.00363617
423	0.00284023	423	0.001523742	423	0.00237736	423	0.00435048
424	0.00323002	424	0.001651587	424	0.00283905	424	0.00473852
425	0.00381437	425	0.001910976	425	0.00314641	425	0.00567706
426	0.00428632	426	0.002224514	426	0.00368717	426	0.00651958
427	0.00485992	427	0.002328487	427	0.00413371	427	0.00733345
428	0.00551815	428	0.002507177	428	0.00476937	428	0.00848614
429	0.00620405	429	0.002976403	429	0.00527471	429	0.00972217
430	0.00697009	430	0.003186277	430	0.00608336	430	0.01117161
431	0.00780336	431	0.003853514	431	0.00702116	431	0.01292855
432	0.00901614	432	0.003942852	432	0.00811387	432	0.0147308
433	0.01014415	433	0.004700351	433	0.00912351	433	0.01657173
434	0.01113295	434	0.005152639	434	0.01041976	434	0.01889538
435	0.01258445	435	0.005745307	435	0.01165766	435	0.02169081
436	0.01408659	436	0.006405943	436	0.01330997	436	0.02431066
437	0.01573917	437	0.00709713	437	0.01520378	437	0.02746114
438	0.01761303	438	0.007776559	438	0.01701638	438	0.03065163
439	0.01964849	439	0.00876945	439	0.01916489	439	0.03470517
440	0.02159511	440	0.00946308	440	0.02151252	440	0.03856662
441	0.02428299	441	0.010380504	441	0.02457883	441	0.04336558

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

442	0.02681941	442	0.011495082	442	0.02765392	442	0.04934339
443	0.02962092	443	0.012755696	443	0.03139975	443	0.05600788
444	0.03248043	444	0.01393293	444	0.0359593	444	0.06388219
445	0.03519613	445	0.015263843	445	0.04031923	445	0.07184757
446	0.03846257	446	0.016787162	446	0.04569625	446	0.08117804
447	0.04096931	447	0.018145938	447	0.05144823	447	0.09014898
448	0.04306198	448	0.019520364	448	0.05723918	448	0.09967813
449	0.0447472	449	0.020286206	449	0.0633239	449	0.10607028
450	0.04556712	450	0.021392832	450	0.06854461	450	0.11277744
451	0.04595666	451	0.021939482	451	0.0714554	451	0.11604024
452	0.04572651	452	0.022683455	452	0.07266914	452	0.11800975
453	0.04471914	453	0.022593505	453	0.0738028	453	0.11642049
454	0.04291404	454	0.022447739	454	0.07153071	454	0.11139419
455	0.04105556	455	0.022777237	455	0.06896785	455	0.10754579
456	0.03811982	456	0.022216784	456	0.06330489	456	0.09837489
457	0.03562674	457	0.022043693	457	0.05824701	457	0.08986993
458	0.03352027	458	0.021810388	458	0.0535782	458	0.08233516
459	0.03104115	459	0.021001775	459	0.04919701	459	0.07419164
460	0.02877735	460	0.020553494	460	0.04573482	460	0.06800118
461	0.02701884	461	0.019636726	461	0.04249681	461	0.06291987
462	0.02542243	462	0.018939095	462	0.03919042	462	0.05929344
463	0.02386654	463	0.017854421	463	0.03750666	463	0.05624263
464	0.02323583	464	0.017235163	464	0.03607939	464	0.05352673
465	0.02237062	465	0.016701721	465	0.03514026	465	0.05196003
466	0.02145449	466	0.016138983	466	0.03407968	466	0.05009444
467	0.02060062	467	0.015605832	467	0.03252153	467	0.04837317
468	0.02004296	468	0.015184963	468	0.03175753	468	0.04606763
469	0.01913579	469	0.014582058	469	0.03019478	469	0.04336978
470	0.01831492	470	0.014307015	470	0.02892407	470	0.04105554
471	0.01763252	471	0.014390655	471	0.0275049	471	0.03907033
472	0.01676273	472	0.013860612	472	0.02597168	472	0.03622529
473	0.0160196	473	0.013747569	473	0.02447486	473	0.03409675
474	0.01549324	474	0.013367617	474	0.02328063	474	0.03186172
475	0.01499717	475	0.013066171	475	0.02234286	475	0.03007791
476	0.0147536	476	0.012813325	476	0.0215959	476	0.02880925
477	0.01437929	477	0.012734992	477	0.02073985	477	0.0280671
478	0.01449476	478	0.012427644	478	0.02037322	478	0.02735265
479	0.0143517	479	0.012313725	479	0.02009181	479	0.02716196
480	0.01460703	480	0.012326214	480	0.02008486	480	0.02707017
481	0.01492418	481	0.012238414	481	0.020046	481	0.02702707
482	0.01521481	482	0.012552166	482	0.02017244	482	0.02759566

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

483	0.01559436	483	0.012533676	483	0.0205237	483	0.02765847
484	0.01601767	484	0.012692955	484	0.02080461	484	0.02798012
485	0.01646318	485	0.013036247	485	0.02120712	485	0.0284917
486	0.01705365	486	0.013328716	486	0.02159438	486	0.02878176
487	0.01747334	487	0.013728861	487	0.02178646	487	0.02930587
488	0.01801667	488	0.01409538	488	0.02226958	488	0.02961803
489	0.01861465	489	0.014639716	489	0.02262264	489	0.03028363
490	0.01921061	490	0.014830347	490	0.0233427	490	0.03070511
491	0.01977841	491	0.015380132	491	0.02365098	491	0.03126716
492	0.02052816	492	0.015786368	492	0.02434471	492	0.03194576
493	0.0211263	493	0.016206602	493	0.02501123	493	0.03263837
494	0.02171926	494	0.016835057	494	0.0253082	494	0.03340684
495	0.02249008	495	0.0173745	495	0.02610214	495	0.03429182
496	0.02312681	496	0.017708228	496	0.02665476	496	0.03498111
497	0.02383649	497	0.018210918	497	0.02733482	497	0.03574912
498	0.02453754	498	0.018643935	498	0.02783774	498	0.0363985
499	0.0251057	499	0.01911616	499	0.02893114	499	0.03743984
500	0.02569185	500	0.019634568	500	0.02913126	500	0.03793873
501	0.02642985	501	0.020090814	501	0.02990588	501	0.03858074
502	0.02685453	502	0.020482548	502	0.03023504	502	0.03908467
503	0.02759227	503	0.020976	503	0.03108628	503	0.03991053
504	0.027995	504	0.021307651	504	0.03152262	504	0.04041202
505	0.02847596	505	0.021801234	505	0.03199839	505	0.04084538
506	0.02894993	506	0.022275489	506	0.03266855	506	0.04134781
507	0.02934951	507	0.022492478	507	0.0328268	507	0.04160497
508	0.02981873	508	0.022872674	508	0.03318251	508	0.042196
509	0.03013749	509	0.023123279	509	0.03352524	509	0.04247003
510	0.0306092	510	0.023567568	510	0.03413262	510	0.04271982
511	0.03071542	511	0.023677099	511	0.03401884	511	0.0431391
512	0.03108771	512	0.024212425	512	0.03460324	512	0.04367616
513	0.03141549	513	0.02440544	513	0.03473219	513	0.04360574
514	0.03174622	514	0.024677839	514	0.03516975	514	0.04385434
515	0.03196942	515	0.024920025	515	0.03527635	515	0.04405471
516	0.03225069	516	0.025232141	516	0.03554993	516	0.04428588
517	0.03257156	517	0.025541935	517	0.0362482	517	0.04460878
518	0.03271217	518	0.025690617	518	0.03620873	518	0.04470516
519	0.03291915	519	0.02589792	519	0.03618856	519	0.04476369
520	0.03310497	520	0.026306333	520	0.0365832	520	0.04527498
521	0.03339934	521	0.026463848	521	0.03673168	521	0.04531308
522	0.03360345	522	0.02676387	522	0.03704148	522	0.04547969
523	0.03345275	523	0.026949623	523	0.03693986	523	0.04561756

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

524	0.03393679	524	0.027337911	524	0.03747613	524	0.04583495
525	0.03405433	525	0.027345277	525	0.03732374	525	0.04571766
526	0.03412805	526	0.02774563	526	0.03764799	526	0.04602094
527	0.03433812	527	0.027910852	527	0.03778242	527	0.04603161
528	0.03463634	528	0.028355008	528	0.03805751	528	0.0463175
529	0.03480618	529	0.028444319	529	0.03821741	529	0.04642216
530	0.03499223	530	0.028741306	530	0.03831445	530	0.0464476
531	0.0351904	531	0.02905159	531	0.03877923	531	0.04672466
532	0.03536074	532	0.029322764	532	0.03885742	532	0.04677459
533	0.03560111	533	0.029485518	533	0.03912966	533	0.04692557
534	0.03583317	534	0.029812431	534	0.03937142	534	0.0468679
535	0.03590764	535	0.030037524	535	0.0394768	535	0.04715033
536	0.0363517	536	0.030366958	536	0.03954438	536	0.0474835
537	0.03666781	537	0.03085107	537	0.04000958	537	0.04759195
538	0.03670625	538	0.031060894	538	0.04012794	538	0.04762519
539	0.03690618	539	0.031428806	539	0.04036506	539	0.04791941
540	0.03708538	540	0.031865291	540	0.0406193	540	0.04813334
541	0.03763656	541	0.032173611	541	0.04100824	541	0.04814895
542	0.03771855	542	0.032479117	542	0.04118216	542	0.04842535
543	0.03798016	543	0.03280105	543	0.04140463	543	0.04836103
544	0.03832572	544	0.033390854	544	0.04194892	544	0.04881059
545	0.0385813	545	0.033573933	545	0.04182277	545	0.0487596
546	0.03872742	546	0.034024774	546	0.04238614	546	0.04892614
547	0.03917626	547	0.034543079	547	0.04241046	547	0.04903475
548	0.03928969	548	0.034919662	548	0.04283583	548	0.04926588
549	0.03961488	549	0.035447606	549	0.04314815	549	0.04920302
550	0.03992356	550	0.035653869	550	0.0432022	550	0.04924416
551	0.04028524	551	0.036252022	551	0.0436728	551	0.04936833
552	0.04057134	552	0.036826881	552	0.04417892	552	0.04968266
553	0.04104322	553	0.037255577	553	0.04429437	553	0.04979233
554	0.04091826	554	0.037795769	554	0.04445069	554	0.04984493
555	0.04160782	555	0.038378383	555	0.04484945	555	0.05000594
556	0.04176739	556	0.038853962	556	0.04495829	556	0.05012248
557	0.04203408	557	0.039419471	557	0.04548775	557	0.05008293
558	0.04254641	558	0.039811293	558	0.04583215	558	0.05026295
559	0.04274637	559	0.04053568	559	0.04604182	559	0.05023639
560	0.04304078	560	0.041021953	560	0.04663704	560	0.05036669
561	0.04347464	561	0.041592815	561	0.04691218	561	0.05042035
562	0.043748	562	0.042205965	562	0.04715883	562	0.0507255
563	0.04443852	563	0.043044273	563	0.04756169	563	0.05092749
564	0.04468311	564	0.043535569	564	0.04804669	564	0.05076086

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

565	0.04502717	565	0.044282601	565	0.04843699	565	0.05073328
566	0.04528085	566	0.044918276	566	0.04880966	566	0.05102968
567	0.04556626	567	0.045567849	567	0.04920943	567	0.05082479
568	0.04580541	568	0.046225496	568	0.04928338	568	0.05093277
569	0.04630769	569	0.046966039	569	0.04973233	569	0.05097821
570	0.04663525	570	0.047635223	570	0.05000077	570	0.05092527
571	0.04699609	571	0.048236413	571	0.05050644	571	0.05091478
572	0.04752061	572	0.049146924	572	0.05104378	572	0.05102582
573	0.04780625	573	0.049866596	573	0.05126521	573	0.0510949
574	0.0480773	574	0.050612397	574	0.05196039	574	0.05099338
575	0.04827817	575	0.051480299	575	0.05196851	575	0.05126154
576	0.04875132	576	0.052263677	576	0.05269226	576	0.05093904
577	0.04915122	577	0.053011943	577	0.05312228	577	0.05099413
578	0.04923883	578	0.053506928	578	0.05310494	578	0.05095438
579	0.0496445	579	0.054268948	579	0.05385807	579	0.05079694
580	0.05004596	580	0.055263301	580	0.05410121	580	0.05099803
581	0.05024305	581	0.055793353	581	0.05455335	581	0.05092586
582	0.05058721	582	0.056645011	582	0.05487995	582	0.05095148
583	0.05086379	583	0.057265151	583	0.05542918	583	0.05050819
584	0.05114274	584	0.058200011	584	0.05580985	584	0.05067462
585	0.05117432	585	0.058533002	585	0.05608584	585	0.05061263
586	0.05167648	586	0.05945603	586	0.05676315	586	0.05079813
587	0.05163367	587	0.060074069	587	0.05664618	587	0.05071098
588	0.05175094	588	0.060839871	588	0.05691463	588	0.0504344
589	0.05209072	589	0.061098595	589	0.05724712	589	0.05003249
590	0.05200318	590	0.061898645	590	0.05750518	590	0.05002848
591	0.05210844	591	0.062706066	591	0.05806783	591	0.04987532
592	0.05227562	592	0.063017073	592	0.05801597	592	0.04986732
593	0.0523631	593	0.063430205	593	0.05830192	593	0.04957901
594	0.0522677	594	0.064210745	594	0.05845901	594	0.04943292
595	0.0523365	595	0.064685801	595	0.05884679	595	0.04921389
596	0.05222289	596	0.064822972	596	0.05886696	596	0.04904174
597	0.0522934	597	0.065235572	597	0.05906826	597	0.04883138
598	0.05229048	598	0.065693306	598	0.05920734	598	0.04860823
599	0.05224508	599	0.06615626	599	0.0594548	599	0.04824751
600	0.05199786	600	0.066582075	600	0.05957971	600	0.04815802
601	0.05222769	601	0.066676872	601	0.05954274	601	0.04782758
602	0.05179438	602	0.066945435	602	0.05915264	602	0.04748007
603	0.05154615	603	0.066923631	603	0.05937699	603	0.04714915
604	0.05142591	604	0.067144321	604	0.05911598	604	0.04691028
605	0.05128418	605	0.067318328	605	0.0593708	605	0.04638569

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

606	0.05100703	606	0.067634632	606	0.05925828	606	0.04638003
607	0.05066672	607	0.067610364	607	0.05892595	607	0.04603151
608	0.05048951	608	0.067701385	608	0.0589414	608	0.04551953
609	0.04999165	609	0.067453798	609	0.05881666	609	0.04510676
610	0.04983444	610	0.06764124	610	0.05855613	610	0.04481596
611	0.04917357	611	0.067123744	611	0.05816119	611	0.04414214
612	0.04903645	612	0.067213826	612	0.0578519	612	0.04362409
613	0.04871092	613	0.067278525	613	0.05805319	613	0.04335326
614	0.04825399	614	0.066712695	614	0.05769621	614	0.04289579
615	0.04766523	615	0.066648722	615	0.05726871	615	0.04243123
616	0.04727989	616	0.066120147	616	0.05653688	616	0.04199406
617	0.04666196	617	0.065931055	617	0.05634443	617	0.04138271
618	0.0462679	618	0.065707124	618	0.05607449	618	0.04112198
619	0.04593191	619	0.065163929	619	0.0556213	619	0.04038977
620	0.04494775	620	0.064830346	620	0.05477704	620	0.04011287
621	0.0444894	621	0.064073621	621	0.05442415	621	0.03951063
622	0.04406753	622	0.063601579	622	0.05437155	622	0.03873584
623	0.04355326	623	0.063279785	623	0.05325177	623	0.03847858
624	0.04320558	624	0.062877061	624	0.0529916	624	0.03802799
625	0.04240633	625	0.062127361	625	0.05229779	625	0.03737284
626	0.04162837	626	0.06125963	626	0.05135581	626	0.03685257
627	0.04100497	627	0.060924739	627	0.05107433	627	0.03608979
628	0.04049589	628	0.060318452	628	0.05057827	628	0.03553939
629	0.03975677	629	0.059648541	629	0.04981959	629	0.03506903
630	0.03925446	630	0.058994694	630	0.04948651	630	0.03440847
631	0.03838328	631	0.058158975	631	0.0484539	631	0.03388099
632	0.03780058	632	0.057497652	632	0.04778258	632	0.03337965
633	0.03716023	633	0.05684524	633	0.04707991	633	0.03288214
634	0.03648155	634	0.055930134	634	0.04621211	634	0.03215218
635	0.03575117	635	0.05517014	635	0.04550374	635	0.0316585
636	0.03508753	636	0.054392666	636	0.04480048	636	0.03104433
637	0.0343599	637	0.05326135	637	0.04417899	637	0.03048942
638	0.03371693	638	0.052395662	638	0.04311578	638	0.02984869
639	0.03307483	639	0.051568859	639	0.04267879	639	0.02934058
640	0.03232666	640	0.050881676	640	0.04169547	640	0.0286181
641	0.03170812	641	0.049843382	641	0.0408616	641	0.02814282
642	0.03104471	642	0.048978306	642	0.04031634	642	0.02760489
643	0.03035194	643	0.047857813	643	0.03953275	643	0.02705194
644	0.02964971	644	0.047071038	644	0.03876688	644	0.02640786
645	0.02912098	645	0.04639525	645	0.03810891	645	0.02578634
646	0.02834672	646	0.04540962	646	0.03721642	646	0.02520623

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

647	0.02775168	647	0.044535527	647	0.03652484	647	0.02469175
648	0.02712613	648	0.043910884	648	0.03598292	648	0.02424237
649	0.02662284	649	0.042974259	649	0.03500915	649	0.02369709
650	0.02586363	650	0.042146591	650	0.03436371	650	0.02308277
651	0.02529179	651	0.041093253	651	0.03347765	651	0.02250076
652	0.02458977	652	0.040417129	652	0.03304464	652	0.02210346
653	0.02409119	653	0.039303619	653	0.03229078	653	0.02150545
654	0.02351897	654	0.038881657	654	0.0313659	654	0.02111703
655	0.02280753	655	0.037936186	655	0.03092575	655	0.02058173
656	0.02234871	656	0.037114811	656	0.03024596	656	0.02006143
657	0.02168947	657	0.036060987	657	0.02946917	657	0.01947774
658	0.02106555	658	0.035359057	658	0.02880679	658	0.01896003
659	0.02063379	659	0.034407274	659	0.02811506	659	0.01849386
660	0.02015016	660	0.033793266	660	0.02758015	660	0.01814608
661	0.01964448	661	0.03302401	661	0.02682771	661	0.01755859
662	0.01896252	662	0.032507692	662	0.02619189	662	0.01727138
663	0.01850218	663	0.03151935	663	0.02555727	663	0.01675159
664	0.01807387	664	0.030748782	664	0.02476899	664	0.0161926
665	0.01746511	665	0.029977263	665	0.02417398	665	0.01582558
666	0.01724036	666	0.029240465	666	0.0237324	666	0.01530659
667	0.01652411	667	0.028635105	667	0.02316859	667	0.01496558
668	0.01620732	668	0.028026433	668	0.02254703	668	0.01469474
669	0.0156813	669	0.027117218	669	0.02197342	669	0.01428838
670	0.01514658	670	0.026355589	670	0.02128617	670	0.01375013
671	0.01479489	671	0.025725495	671	0.02081376	671	0.01346882
672	0.01422971	672	0.02502841	672	0.02015343	672	0.01306122
673	0.01397503	673	0.024587007	673	0.01968759	673	0.01282574
674	0.01358828	674	0.023953861	674	0.01924882	674	0.01243406
675	0.01315438	675	0.02343116	675	0.01875978	675	0.01203029
676	0.01292534	676	0.022765849	676	0.01837636	676	0.01167187
677	0.01237468	677	0.022061682	677	0.01775009	677	0.01127104
678	0.01205125	678	0.021334316	678	0.01710981	678	0.01101566
679	0.01172184	679	0.020809097	679	0.01683037	679	0.01078006
680	0.01141807	680	0.020380816	680	0.01639387	680	0.01030327
681	0.01100895	681	0.019684244	681	0.01591704	681	0.01018849
682	0.01072051	682	0.019178365	682	0.01545967	682	0.00983618
683	0.0103805	683	0.018658669	683	0.01504592	683	0.00958845
684	0.01004581	684	0.018071097	684	0.01452208	684	0.00928751
685	0.00978055	685	0.017692146	685	0.01434591	685	0.00909236
686	0.00950171	686	0.017182531	686	0.01369427	686	0.00880512
687	0.00913787	687	0.01672882	687	0.01332374	687	0.00850967

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

688	0.00886636	688	0.016260732	688	0.01303363	688	0.00835028
689	0.00863919	689	0.015669736	689	0.01272052	689	0.00803828
690	0.00831327	690	0.01521793	690	0.01229481	690	0.00780582
691	0.00810277	691	0.01468599	691	0.01195496	691	0.00751806
692	0.00782602	692	0.014362222	692	0.01159883	692	0.00728502
693	0.0076205	693	0.013845443	693	0.01124906	693	0.00691661
694	0.00741749	694	0.013697217	694	0.01092551	694	0.00708632
695	0.00703171	695	0.013350349	695	0.01059177	695	0.0066325
696	0.00687363	696	0.012800042	696	0.01037745	696	0.00651386
697	0.00679748	697	0.012667923	697	0.00994237	697	0.00644091
698	0.00657215	698	0.01216469	698	0.00964068	698	0.00606862
699	0.00628321	699	0.011548884	699	0.00934451	699	0.00585822
700	0.00629016	700	0.011426851	700	0.00909462	700	0.00571666
701	0.00604756	701	0.011052231	701	0.00899778	701	0.00550778
702	0.00565816	702	0.010724723	702	0.00862593	702	0.00532373
703	0.00562246	703	0.010344739	703	0.00829346	703	0.00533668
704	0.00544969	704	0.010002565	704	0.00806807	704	0.00526833
705	0.00520697	705	0.009940926	705	0.00784779	705	0.00515481
706	0.00519923	706	0.009273135	706	0.00772028	706	0.00471373
707	0.00488456	707	0.008961019	707	0.00737524	707	0.00451875
708	0.00470099	708	0.009145168	708	0.00736947	708	0.00464622
709	0.00461572	709	0.008624327	709	0.0070335	709	0.00444903
710	0.00425178	710	0.008259735	710	0.00662201	710	0.00425202
711	0.00432126	711	0.008134733	711	0.00667959	711	0.00412436
712	0.00415335	712	0.007922432	712	0.00642098	712	0.00405291
713	0.00412286	713	0.007694676	713	0.00624566	713	0.00389901
714	0.00405859	714	0.007497861	714	0.0060618	714	0.00388021
715	0.00376585	715	0.007101698	715	0.00568564	715	0.00343601
716	0.00385938	716	0.007179158	716	0.00588704	716	0.00355695
717	0.00356233	717	0.00685208	717	0.00541535	717	0.00347696
718	0.00353307	718	0.006583441	718	0.00532401	718	0.00342455
719	0.00345117	719	0.006372276	719	0.00521322	719	0.00341887
720	0.00328591	720	0.006137632	720	0.00480237	720	0.00309718
721	0.00328095	721	0.005905544	721	0.00488819	721	0.00314785
722	0.00310163	722	0.005989224	722	0.00470987	722	0.00305654
723	0.00303008	723	0.005501381	723	0.00459877	723	0.002752
724	0.00299205	724	0.005385523	724	0.00463998	724	0.00287941
725	0.00285091	725	0.005307364	725	0.00420821	725	0.00275575
726	0.00274486	726	0.005077512	726	0.00423396	726	0.00257979
727	0.00258439	727	0.005112547	727	0.00404431	727	0.00264687
728	0.00252068	728	0.004882111	728	0.00389271	728	0.00232358

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

729	0.0025543	729	0.004721708	729	0.00390532	729	0.0025115
730	0.00250629	730	0.004299412	730	0.00368571	730	0.0021684
731	0.0024284	731	0.004413165	731	0.00363581	731	0.00224466
732	0.00235677	732	0.004392917	732	0.00357857	732	0.00235168
733	0.00230738	733	0.004368491	733	0.00342647	733	0.00243838
734	0.00207161	734	0.003762519	734	0.00325133	734	0.00183994
735	0.00207604	735	0.00406697	735	0.00327432	735	0.0021788
736	0.00223532	736	0.003720521	736	0.00346045	736	0.00187261
737	0.00215625	737	0.003686207	737	0.00325618	737	0.00196193
738	0.00186972	738	0.003380802	738	0.00298545	738	0.00181479
739	0.00189227	739	0.003361273	739	0.00282384	739	0.00175342
740	0.00195158	740	0.003393472	740	0.00294363	740	0.00171459
741	0.00169399	741	0.003301323	741	0.0026439	741	0.0017363
742	0.00182496	742	0.003361265	742	0.00270111	742	0.00183501
743	0.001655	743	0.003197061	743	0.00284927	743	0.00166052
744	0.00165283	744	0.003190426	744	0.00253127	744	0.00168696
745	0.00157955	745	0.002951851	745	0.00247057	745	0.00158031
746	0.00152242	746	0.002728836	746	0.0023718	746	0.00145564
747	0.00163164	747	0.002740436	747	0.00245082	747	0.00146821
748	0.00151804	748	0.002561216	748	0.00230911	748	0.00135272
749	0.0014236	749	0.00265871	749	0.00214337	749	0.00134652
750	0.0014627	750	0.002459073	750	0.00221502	750	0.00152946
751	0.0013443	751	0.002248539	751	0.0020947	751	0.00111357
752	0.00122525	752	0.002425681	752	0.00188822	752	0.00122222
753	0.0013242	753	0.002441549	753	0.00197125	753	0.00131284
754	0.00127031	754	0.00225995	754	0.00201932	754	0.00121347
755	0.00129191	755	0.001964725	755	0.0019657	755	0.00120374
756	0.00140868	756	0.002168101	756	0.00197008	756	0.00132688
757	0.00106679	757	0.002356981	757	0.00177175	757	0.00127375
758	0.00130681	758	0.001944449	758	0.00186185	758	0.00121926
759	0.0012331	759	0.002065911	759	0.00188462	759	0.00114627
760	0.00111099	760	0.00176706	760	0.00165975	760	0.00099963
761	0.00142735	761	0.00199484	761	0.00179763	761	0.00112908
762	0.00120151	762	0.00188128	762	0.0016951	762	0.00121828
763	0.00086382	763	0.001523887	763	0.00148835	763	0.00078126
764	0.00102312	764	0.001651228	764	0.00144727	764	0.00099846
765	0.00113609	765	0.001414776	765	0.00155003	765	0.00084517
766	0.00072939	766	0.001651348	766	0.00134313	766	0.0009702
767	0.00086201	767	0.00150991	767	0.00128555	767	0.00103776
768	0.00081945	768	0.001377695	768	0.00137708	768	0.0008114
769	0.00096682	769	0.001585066	769	0.00166619	769	0.00097336

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

770	0.00104297	770	0.001491376	770	0.00128703	770	0.00108685
771	0.00095571	771	0.001302427	771	0.00132524	771	0.00082035
772	0.00089407	772	0.001381565	772	0.00125798	772	0.00084808
773	0.00086978	773	0.001197137	773	0.00104587	773	0.00023932
774	0.00083443	774	0.001368941	774	0.0012171	774	0.00107297
775	0.00086066	775	0.001262845	775	0.00131499	775	0.00080052
776	0.00088633	776	0.001108468	776	0.00126403	776	0.00070595
777	0.00070636	777	0.001311106	777	0.00103786	777	0.00072715
778	0.00112161	778	0.001279239	778	0.00109702	778	0.00085279
779	0.00086907	779	0.001322083	779	0.0011577	779	0.00085863
780	0.00078604	780	0.000980483	780	0.00131341	780	0.00052752
781	0.00089485	781	0.000650817	781	0.00094708	781	0.0004358
782	0.00054696	782	0.00094904	782	0.00109606	782	0.00073728
783	0.00064031	783	0.001119052	783	0.0010909	783	0.00055702
784	0.00095689	784	0.001113969	784	0.00119624	784	0.00063288
785	0.00077833	785	0.001251762	785	0.0008292	785	0.00084467
786	0.00097011	786	0.000765579	786	0.00121966	786	0.00038153
787	0.0008231	787	0.000890546	787	0.00084087	787	0.00103042
788	0.0006167	788	0.001215556	788	0.00086271	788	0.00090193
789	0.00083975	789	0.000941969	789	0.00138893	789	0.00054611
790	0.00107279	790	0.001203524	790	0.00119199	790	0.00083545
791	0.0007856	791	0.000751749	791	0.00103593	791	0.00086031
792	0.00048224	792	0.000653862	792	0.00076536	792	0.00035613
793	0.00084579	793	0.000518341	793	0.00119332	793	0.00037589
794	0.0008071	794	0.000725899	794	0.0008995	794	0.00070125
795	0.00053204	795	0.001018824	795	0.00112414	795	0.00105331
796	0.00072618	796	0.000658041	796	0.00087451	796	0.00025545
797	0.0005854	797	0.000655219	797	0.00106792	797	0.00064172
798	0.00108762	798	0.001051714	798	0.00102374	798	0.00082999
799	0.00109265	799	0.000296977	799	0.00132553	799	0.00019591
800	0.00074564	800	0.001058825	800	0.00109532	800	0.00099902
801	0.0013362	801	0.001161552	801	0.00176237	801	0.00079411
802	0.00082627	802	0.000641862	802	0.0009851	802	0.00083983
803	0.00024028	803	0.00084911	803	0.0007644	803	0.00066613
804	0.00090514	804	0.000647512	804	0.00095982	804	0.00080145
805	0.00059639	805	0.000573287	805	0.00073406	805	0.00029188
806	0.00086938	806	0.000892733	806	0.00085262	806	0.00074789
807	0.00091807	807	0.000125755	807	0.0010717	807	0.00019994
808	0.00066271	808	0.001160403	808	0.00117363	808	0.00069471
809	0.00040504	809	0.000534616	809	0.00140776	809	0.00038291
810	0.00063121	810	0.000308143	810	0.00081926	810	0.00048202

Table A.4 (continued): Experimentally measured SPD and technical data of L1 3800K, L2 2700K, L2 3800K, L2 6000K.

811	0.00095727	811	0.000440349	811	0.00143562	811	0.00057371
812	0.00124583	812	0.000446916	812	0.00117124	812	0.00031699
813	0.00095264	813	0.000345786	813	0.00087174	813	0.00079085
814	0.00067851	814	0.001005961	814	0.00115915	814	0.00061507
815	0.00070016	815	0.000962337	815	0.00085825	815	0.00115181
816	0.00111188	816	0.00059471	816	0.00115223	816	-6.40E-06
817	0.0010831	817	0.000718942	817	0.00128076	817	0.00052621
818	0.00137196	818	0.000708977	818	0.00084622	818	0.00070397
819	0.00084956	819	0.000417041	819	0.00098272	819	0.00105121
820	0.00062152	820	-0.0001607	820	0.00078561	820	-7.85E-05
821	0.00099191	821	0.000414624	821	0.00179005	821	0.00083951
822	0.0004119	822	0.000123567	822	0.00043764	822	0.00016061
823	0.00133928	823	0.000807465	823	0.00235525	823	0.00018761
824	0.00056065	824	0.000181575	824	0.00080018	824	0.00083479
825	0.00080524	825	0.000437922	825	0.00097905	825	0.00046225
826	0.00098848	826	-6.44E-05	826	0.00120681	826	0.00016243
827	0.00060131	827	-3.89E-07	827	0.00133713	827	0.00067516
828	0.00095542	828	0.000464366	828	0.00149846	828	0.00042241
829	0.00171318	829	0.001099531	829	0.00163249	829	0.0013442
830	0.00100129	830	0.000616757	830	0.00096278	830	0.00066093
831	0.00177342	831	0.000750687	831	0.00169691	831	0.00102476
832	0.00112472	832	0.001335456	832	0.00184493	832	0.00129016
833	0.00123022	833	0.000994239	833	0.00148224	833	0.00119081
834	0.00098011	834	0.002185995	834	0.00192033	834	0.00187325
835	0.00048819	835	0.000568456	835	0.00089513	835	0.00019453
836	0.00108174	836	0.001108514	836	0.0006904	836	0.00169413
837	0.00129083	837	0.000444582	837	0.00209972	837	0.00085371
838	0.00146727	838	0.000322829	838	0.0012077	838	0.00068764
839	0.00128002	839	0.000225607	839	0.00157725	839	0.00032562
840	0.00027737	840	0.000541796	840	0.0007451	840	0.00100757
841	0.00141176	841	0.000884445	841	0.00082131	841	0.00104895
842	0.00092977	842	-0.00012601	842	0.0010953	842	0.00036472
843	0.00161356	843	0.001648166	843	0.00052454	843	0.00147886
844	0.00141008	844	0.000977313	844	0.00195303	844	0.00109473
845	0.00158792	845	-0.00080214	845	0.00200055	845	9.65E-05
846	0.00211812	846	0.001363518	846	0.00248493	846	0.00153736
847	0.00215343	847	-7.36E-05	847	0.00212496	847	9.38E-05
848	0.00171523	848	0.001118712	848	0.00195953	848	0.0013093
849	0.00154652	849	0.000520996	849	0.00247771	849	0.00107526
850	0.00213411	850	0.000806166	850	0.00291104	850	-0.0002067

APPENDIX B.

1	How do you currently feel? Please mark the most suitable option	
	Extremely alert	
	Very alert	
	Alert	
	Quite alert	
	Neither alert nor sleepy	
	Some signs of sleepiness	
	Sleepy but not making an effort to stay awake	
	Sleepy but making some effort to stay awake	
	Very sleepy, making a considerable effort to stay awake, fighting sleep	
	Extremely sleepy, unable to stay awake	

		Very poor	Poor	Moderate	Good	Very good
2	How satisfied are you with the overall comfort of your office furniture (chair, desk, equipment arrangement, etc.)?					
	How satisfied are you with the available space for desk/individual work arrangement?					

3	What is your age group?	20-30	30-40	40+

4	What is your gender?	Female	Male

5	Do you wear contact lenses or glasses or if you have any eye disorder, please specify.	Yes	No

		Very poor	Poor	Moderate	Good	Very good
6	Do you feel concentrated?					
	Do you feel nervous?					
	Do you feel inspired?					
	Do you feel determined?					
	Do you feel afraid?					
	Do you feel upset?					
	Do you feel ashamed?					
	Do you feel physically well right now?					
	Do you feel mentally well right now?					
	Do you feel motivated to complete the task that you are currently working on?					

Figure B.1: Test and general information with PANAS Questionnaires.

Please answer the tests as quickly as possible. Match the letters in the left column with those in the right column.

L1

	H1				H2				H3		
1	SCBP	PBBP	......	**1**	BP659	SCBP	......	**1**	BP659	BSOP	......
2	PCSS	BB999	......	**2**	PP999	PCSS	......	**2**	PP999	SCBP	......
3	BSOP	PB555	......	**3**	SCBP	BSOP	......	**3**	SCBP	BCSS	......
4	BP659	BB969	......	**4**	BB999	BP659	......	**4**	BB999	PP999	......
5	BCSS	SSPB	......	**5**	PBBP	BCSS	......	**5**	PBBP	PCSS	......
6	GCOD	PB595	......	**6**	BB969	GCOD	......	**6**	BB969	BB969	......
7	PP999	SSCC	......	**7**	SSCC	PP999	......	**7**	SSCC	PBBP	......
8	BB999	BP595	......	**8**	BP595	BB969	......	**8**	BP595	BP659	......
9	BP999	BP999	......	**9**	PCSS	BP999	......	**9**	PCSS	BP999	......
10	BB969	PB559	......	**10**	BP999	BB999	......	**10**	BP999	SSPB	......
11	PBBP	PB556	......	**11**	SSPB	PBBP	......	**11**	SSPB	BP595	......
12	SSCC	00CC	......	**12**	BCSS	SSCC	......	**12**	BCSS	GCOD	......
13	BP595	SCBO	......	**13**	PB555	BP595	......	**13**	PB555	BB999	......
14	PB555	PP999	......	**14**	PB595	PB555	......	**14**	PB595	SSCC	......
15	PB556	SCBP	......	**15**	BSOP	PB556	......	**15**	BSOP	PB559	......
16	PB595	GCOD	......	**16**	PB556	PB595	......	**16**	PB556	SCBO	......
17	SSPB	BSOP	......	**17**	SCBO	SSPB	......	**17**	SCBO	PB555	......
18	PB559	BP659	......	**18**	GCOD	PB559	......	**18**	GCOD	00CC	......
19	SCBO	PCSS	......	**19**	PB559	SCBO	......	**19**	PB559	PB556	......
20	00CC	BCSS	......	**20**	00CC	00CC	......	**20**	00CC	PB595	......

Completion time: ...... **Completion time: ......** **Completion time: ......**

Please answer the tests as quickly as possible. Match the letters in the left column with those in the right column.

L2

	H1				H2				H3		
1	SCBP	BSOP	......	**1**	PBBP	BSOP	......	**1**	GCOD	PBBP	......
2	PCSS	SCBP	......	**2**	BB999	SCBP	......	**2**	PP999	BB999	......
3	BSOP	BCSS	......	**3**	PB555	BCSS	......	**3**	BB999	PB555	......
4	BP659	PP999	......	**4**	BB969	PP999	......	**4**	BSOP	BB969	......
5	BCSS	PCSS	......	**5**	SSPB	PCSS	......	**5**	PBBP	SSPB	......
6	GCOD	BB969	......	**6**	PB595	BB969	......	**6**	SCBP	PB595	......
7	PP999	PBBP	......	**7**	SSCC	PBBP	......	**7**	BP595	SSCC	......
8	BB999	BP659	......	**8**	BP595	BP659	......	**8**	SSCC	BP595	......
9	BP999	BP999	......	**9**	BP999	BP999	......	**9**	PCSS	BP999	......
10	BB969	SSPB	......	**10**	PB559	SSPB	......	**10**	PB555	PB559	......
11	PBBP	BP595	......	**11**	PB556	BP595	......	**11**	SSPB	PB556	......
12	SSCC	GCOD	......	**12**	00CC	GCOD	......	**12**	BP659	00CC	......
13	BP595	BB999	......	**13**	SCBO	BB999	......	**13**	BCSS	SCBO	......
14	PB555	SSCC	......	**14**	PP999	SSCC	......	**14**	PB556	PP999	......
15	PB556	PB559	......	**15**	SCBP	PB559	......	**15**	PB559	SCBP	......
16	PB595	SCBO	......	**16**	GCOD	SCBO	......	**16**	SCBO	GCOD	......
17	SSPB	PB555	......	**17**	BSOP	PB555	......	**17**	PB595	BSOP	......
18	PB559	00CC	......	**18**	BP659	00CC	......	**18**	BP999	BP659	......
19	SCBO	PB556	......	**19**	PCSS	PB556	......	**19**	00CC	PCSS	......
20	00CC	PB595	......	**20**	BCSS	PB595	......	**20**	BB969	BCSS	......

Completion time: ...... **Completion time: ......** **Completion time: ......**

Figure B.2: Q1 Visual Cognitive Matching Performance Test**.**

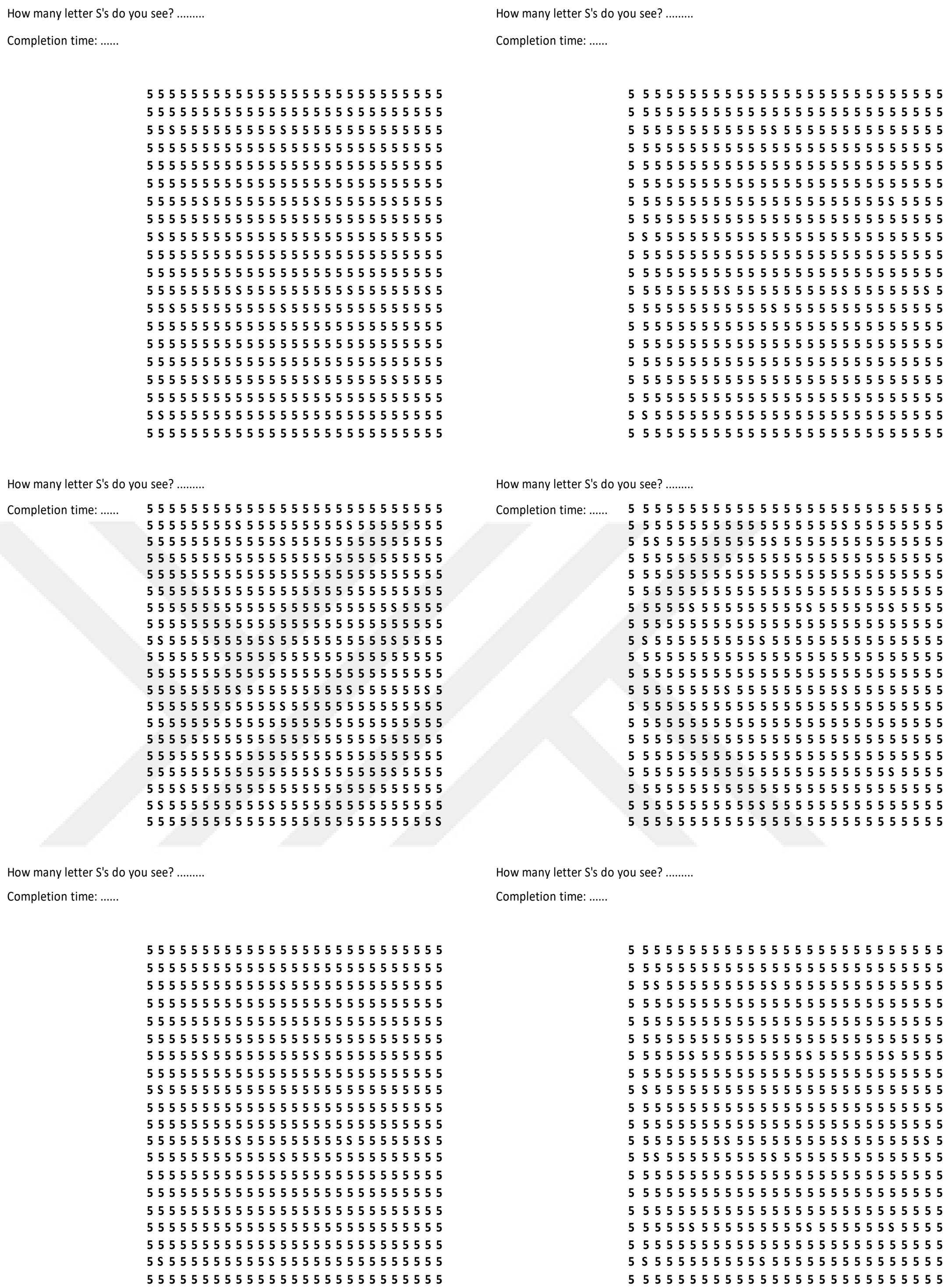


Figure B.3: Q2 Visual Proofreading Task Test**.**

Please respond to your preferences from the options below.

L1

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H1)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H2)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H3)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

Please respond to your preferences from the options below.

L2

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H1)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H2)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

	Very Poor	Poor	Moderate	Good	Very Good
I am satisfied with the current lighting.					
There is an appropriate level of lighting for the task I am currently doing.					
I am satisfied with the color of the light.					
The lighting has bothered during the task.					
The lighting is adequate on my work desk.					

Is the lighting height suitable for you (H3)?	Yes	No
Note: (Do you have any additional suggestions to add)?		

Figure B.4: Questionnaire of survey.

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- **B.Sc. :** 2012, University, Azad University of Tabriz, Electrical Engineering

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- E-Lab remotely controlled physics laboratories (python programming based) certificate of achievement at Instituto Superior Tecnico LISBOA/ Lisbon, PORTUGAL.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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