THE EFFECTS OF WINDOW GLAZING AND DYNAMIC LED LIGHTING ON DAYLIGHT QUALITY, OCCUPANT ALERTNESS AND WORK PERFORMANCE IN OFFICES

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ABSTRACT

THE EFFECTS OF WINDOW GLAZING AND DYNAMIC LED LIGHTING ON DAYLIGHT QUALITY, OCCUPANT ALERTNESS AND WORK PERFORMANCE IN OFFICES

Daylighting positively impacts energy consumption, comfort, health, and performance, leading to the increasing use of fully glazed facades in office buildings. However, selecting the appropriate window glass is critical, as it affects solar radiation, heat gain/loss, and daylight quality. Advanced window glasses improve energy efficiency but may distort daylight's color and spectrum, creating undesirable lighting conditions. The rise of LED lighting, designed to reduce energy use, introduces challenges with its blue light emissions, which can disrupt circadian rhythms. This research integrates daylight and artificial lighting to evaluate their combined effects on cognitive performance, satisfaction, attention, and alertness. Artificial Neural Networks (ANN) and fuzzy logic models were employed to identify optimal lighting conditions, considering illuminance, color temperature, spectral distribution, and glass types. Two offices were tested with ten types of window glass and dynamic LED systems. Results show that dynamic LED lighting systems significantly enhance Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML), particularly in combination with certain glass types. Clear and smart glass provided the best results for task performance and user satisfaction, while photovoltaic and tinted glasses led to lower satisfaction. The effect of lighting conditions was evident in paper-based visual tasks, whereas computer-based tasks were more related to demographic information than lighting conditions. ANN models successfully predicted performance outcomes with an accuracy range of 40% to 93%. Performance classification was successfully achieved through fuzzy logic models, and the methodology of this study offers valuable guidance for future research, providing a framework that can be integrated into building performance evaluation systems.

ÖZET

OFİSLERDE PENCERE CAMI VE DİNAMİK LED AYDINLATMANIN GÜNIŞIĞI KALİTESİ, KULLANICILARIN DİKKATİ VE İŞ PERFORMANSI ÜZERİNE ETKİLERİ

Gün ışığı, enerji tüketimi, konfor, sağlık ve performans üzerinde olumlu bir etkiye sahiptir ve bu nedenle ofis binalarında tamamen cam cephelerin kullanımı artmaktadır. Ancak, doğru cam türünün seçilmesi büyük önem taşır, çünkü camlar güneş radyasyonu, ısı kazancı/kaybı ve gün ışığı kalitesini etkiler. Gelişmiş cam teknolojileri enerji verimliliğini artırırken, gün ışığının renk ve spektrumunu bozarak istenmeyen aydınlatma koşulları oluşturabilir. Enerji tasarrufunu artırmak amacıyla kullanılan LED aydınlatmalar da mavi ışık yayılımı nedeniyle sirkadiyen ritimlerin bozulmasına yol açabilmektedir. Bu araştırma, gün ışığı ve yapay aydınlatmanın bir arada kullanılarak bilişsel performans, memnuniyet, dikkat ve uyanıklık üzerindeki etkilerini değerlendirmeyi amaçlamaktadır. Aydınlatma seviyeleri, renk sıcaklığı, spektral dağılım ve cam türleri dikkate alınarak, en uygun aydınlatma koşullarını belirlemek için Yapay Sinir Ağları (ANN) ve bulanık mantık modelleri kullanılmıştır. İki ofiste, on farklı cam türü ve dinamik LED sistemleri ile deneyler gerçekleştirilmiştir. Sonuçlar, dinamik LED sistemlerinin özellikle bazı cam türleri ile birlikte kullanıldığında Sirkadiyen Uyarım (CS) ve Eşdeğer Melanopik Lüks (EML) değerlerini önemli ölçüde artırdığını göstermektedir. Şeffaf ve akıllı camlar, görev performansı ve kullanıcı memnuniyeti açısından en iyi sonuçları sağlarken, fotovoltaik ve renkli camlar daha düşük memnuniyet düzeylerine yol açmıştır. Aydınlatma koşullarının etkisi, özellikle kağıt bazlı görsel görevlerde belirgin olurken, bilgisayar tabanlı görevlerin aydınlatma koşullarından ziyade demografik bilgilerle daha ilgili olduğu gözlemlenmiştir. ANN modelleri, performans sonuçlarını %40 ile %93 arasında bir doğrulukla tahmin etmede başarılı olmuştur. Performans sınıflandırması bulanık mantık modelleri ile başarıyla yapılmış olup, bu çalışmanın metodolojisi gelecekteki araştırmalar için değerli bir rehber sunarak bina performans değerlendirme sistemlerine entegre edilebilecek bir çerçeve sağlamaktadır.

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CHAPTER 1

INTRODUCTION

Daylight, which has physiological and psychological effects on human metabolism, is dynamic, varying in aspects like color temperature, light intensity, and color throughout the day based on the sun's position. These changes in daylight affect the circadian rhythm and therefore, daylight is crucial for human life.

In the past, people spent the majority of their time outdoors in natural daylight. Nowadays, most of their time is spent indoors in environments lit by artificial light sources such as homes, offices, hospitals, and schools. The human circadian rhythm and internal biological clock are aligned with the Earth's light-dark cycle. Therefore, irregularities may occur in human circadian rhythms depending on the light that they are exposed to indoors. The concept of 'human-centric lighting' emerged to bring the dynamic qualities of sunlight into living and working spaces, aiming to maintain the biological clock and circadian rhythms. Human-centric lighting is the set of technical methods used to obtain the biological effects of daylight in an artificial lighting environment (Houser and Esposito 2021). That is, lighting is designed to balance the human day/night rhythm. With human-centric lighting systems, it is aimed to obtain artificial light in natural light quality and to ensure that human metabolism reacts in artificial lighting conditions as in day-lit environment. The human-centric lighting concept focuses on developing and using lighting systems that support well-being, mood and health rather than an aesthetic perspective (Köseli 2018; Kompier, Smolders, and de Kort 2020).

1.1. Problem Definition

It is known that the effective use of daylight in buildings increases the visual performance of the users, reduces the electrical energy to be spent for lighting, and reduces the cooling loads of the building by reducing the use of electrical light sources and using shading elements (Peter Boyce, Hunter, and Howlett 2003; Heschong, Wright, and Okura 2002; Ihm, Nemri, and Krarti 2009; Konis 2013; Leslie 2003). The benefit of natural lighting is not limited to energy consumption and providing comfort conditions, but it is often emphasized in recent researches that it also affects human health (psychology, eye health, hormone secretion, sleep/wake pattern, behaviors), working performance, students' learning ability, aesthetic judgements of building users and the perception of the physical environment (Andersen, Mardaljevic, and Lockley 2012; L. Bellia, Pedace, and Barbato 2013). These effects occur when the visual, biological and mental benefits of light come together. In recent years, fully glazed facades have been increased in office buildings to provide more daylight indoors. The correct selection of window glass is important because windows are both a source of excessive solar radiation and a source of heat gain/loss. Advancements in technology and concerns about energy efficiency (heating and cooling) have led to the development of multi-layered, film-coated, electrochromic, and even photovoltaic window glass. Research indicates that modern glass facades with low-e, solar coatings, and tinted glass can alter the colour and spectrum of daylight. This can lead to unwanted lighting conditions for users. Innovative glasses produced with technological development should be examined in this context (L. Bellia, Pedace, and Barbato 2013; Laura Bellia and Seraceni 2014).

Although the use of daylight is increased, artificial lighting systems are still needed. Daylight illuminance levels may fall below the desired level due to sky conditions and the design of large buildings. Artificial lighting is necessary when long working hours are planned during the day, especially in working places. In these environments, lighting systems containing LED light sources are often preferred as they offer energy efficient and economical solutions. Despite the high amount of light emitted, the energy consumption values of these lamps are considerably low compared to fluorescents. Lamp life is quite long and maintenance costs are low. Besides these advantages, LED light can have negative effects on human health. These effects include issues such as glare, optical damage, LED flicker, nocturnal exposure to LED light, toxic chemical content of LEDs in detail (Ticleanu and Littlefair 2015). It is known that the energy distribution of the LED light spectrum is higher in the blue wavelength. It has been discussed in recent studies that this may have an effect on the melatonin hormone suppression due to the circadian rhythm. The indicator that expresses this 24-hour cycle (circadian rhythm) is calculated by the percentage of melatonin hormone secretion, in other words the ratio of "circadian stimulus - CS". CL can be calculated with a set of formulas developed with multiple field measurements, depending on the spectral structure of a light source, e.g., LED light or daylight (Rea et al. 2010). In classrooms and offices; colour temperature, illuminance level, spectrum of the light source and circadian rhythm have been associated with the learning performance of students and the work performance, by developing of various methods (L.

Bellia, Pedace, and Barbato 2013; Gentile et al. 2018). These studies have gained importance in recent years and the number of researches in this field has been increasing. The most appropriate and accurate methods are being investigated.

1.2. Purpose of the Study

The main purpose of the study is to correlate the glass type, LED lighting system, illuminance, colour temperature, spectral distribution, and luminance values with the performance of office users. It is aimed to examine which colour temperature, illuminance and glass type the office users prefer to work in, and under which lighting conditions their performance improves. The secondary aim is to correlate the most appropriate use of dynamic LED lighting and the selection of window glass. It is to find the weight values of the effective parameters using statistical methods. For example, it is aimed to achieve results such as the change of spectral distribution affects people's perception of colours on the computer screen more or less than the change of glass type. The third purpose is to predict and classify the performance of office users with artificial intelligence models using the lighting parameters (colour temperature, illuminance, spectrum, luminance etc). This type of classification can enable a human-centric assessment of lighting conditions of the offices. Based on users' preferences and performance, it can be determined which combination of glass type with LED illuminance and colour temperature will optimize satisfaction and cognitive performance in an office setting. This information also supports the protection of human health, as discussed in the literature on the relationship between lighting and health. By employing artificial intelligence methods, a human-centric lighting criterion can be developed through the estimation and classification of user performance and satisfaction. Once established, this criterion could potentially be integrated into environmental performance evaluations of buildings, such as LEED certification. It can have an encouraging guiding effect for the production and use of dynamic LED lighting systems. Preliminary information will be created in terms of users' satisfaction and performance to review the types of glass frequently used in offices and to develop new glass types according to the spectrum properties and permeability of glass companies. When sustainable building design is targeted in the construction industry, suggestions (LED, glass types) from the results of this project can be used.

1.3. Research Questions

- How does the cognitive performance/satisfaction of office workers change in which glass type?
- How does the cognitive performance/satisfaction of office workers change with the LED lighting system at which illuminance level and colour temperature?
- Which glass type should be used with the most suitable LED lighting condition to improve the cognitive performance/satisfaction of office workers?
- How to predict and classify the cognitive performance/satisfaction of office workers according to lighting conditions (LED illuminance level, colour temperature, glass type, external illuminance level, spectral distribution of daylight indoors, daylight colour temperature, etc.)?

1.4. Significance of the Study

Window design becomes important for the most effective use of daylight in offices. The correct selection of the glass used in both conventional windows and glass curtain walls is important in terms of the non-visual effects of daylight on users. LED lighting systems have similar effects. In this study, LED lighting and glass selection will be coped with together and the pleasantness, attention, alertness and work performances of the office users will be related. Thus, by defining the most suitable lighting conditions (illumination level, colour temperature, spectral distribution, glass type), the performance and pleasantness of the users will be predicted with artificial intelligence models (artificial neural networks-ANN and fuzzy logic-fuzzy model) and classified (with fuzzy logic model). For example, there is no method in the literature to predict that the user will show poor work performance in a glass type selected at a certain luminance level and at a specific colour temperature. Such a model may have the potential to be a criterion that can be scored in future standards to be established in our country or in sustainable building rating systems such as LEED. In the general framework, it is aimed to develop a human-oriented criterion by considering the light-human-health relationship.

CHAPTER 2

LITERATURE REVIEW

2.1. Effects of Lighting on Human Beings

Light, which is the energy source for plants for photosynthesis, is also the primary source of life for humans. The vehicle that allows us to visually perceive the world is light. No medium, object, shape, color or texture can be seen without light. We can perceive and define our environment with our other sensory organs, but this perception and identification with our eyes can be much easier and precise at the level of detail. Therefore, the phenomenon of vision plays an important role in the activities of individuals in their daily lives (Boubekri 2014; Brandi 2012; M Knoop et al. 2020).

The relationship between light and human beings involves much more than simple processes such as vision and recognizing objects around us. It is known that lighting has an effect on the human health, biological clock, perception mechanism and psychological conditions. Circadian rhythm, physiological and psychological conditions vary depending on the quantity and quality of the light received at the eye. Therefore, lighting is an area of interest in many sciences from physics to psychology, from electrical engineering to biology (P.R. Boyce 2014; Licht and Wissen 2014; Smolders 2013). In order to structure this complex research area, a framework presenting the different ways in which light can affect human metabolism are shown in Figure 1.1.

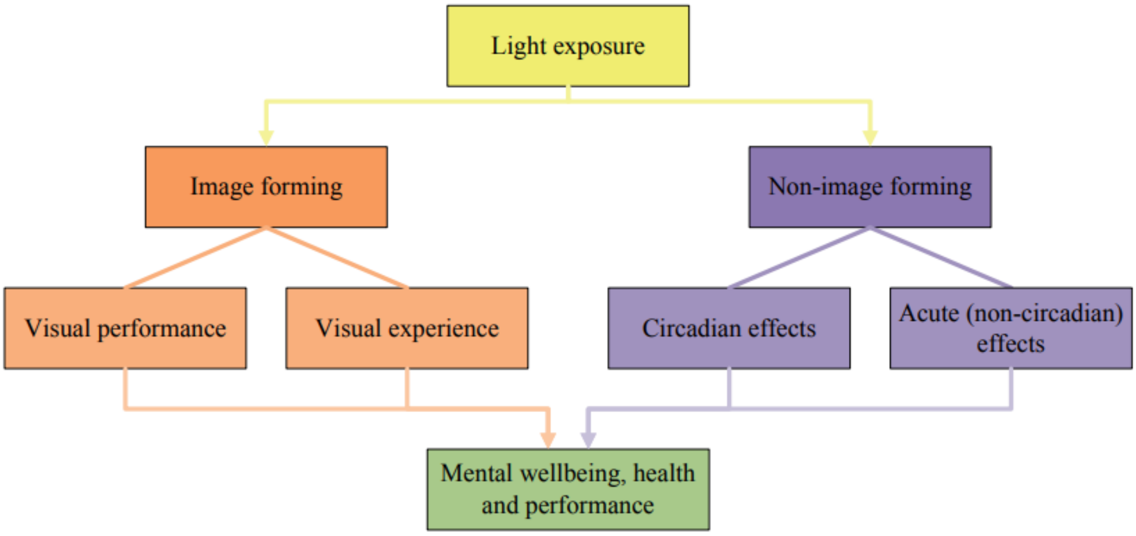


Figure 1.1. Schematic representation of the different routes through which light can affect human functioning (Source: Smolders 2013)

The effect of light on humans can be examined in two different groups as visual and non-visual effects (van Bommel and van den Beld 2004). This effects occur through image forming and non-image forming photoreception (Martine Knoop 2006). By means of photoreceptors in the human retina, photons are absorbed and light information is converted into neural signals. These signals are transmitted to different brain regions through the optic nerve. The path the retina transmits light information to visual brain regions such as the lateral geniculate nucleus (LGN) and visual cortex refers to image-forming photoreception. Through this process, we can visually perceive the world around us by detecting the light reflected from the physical environment and processing it in the relevant area of the brain. On the other hand, the transmission of light reaching the human retina to the area of the brain responsible for the regulation of mood, physiology and behavior constitutes the non-image forming photoreception. This non-visual path affects individuals' biological clocks, their level of alertness and attention, and cognitive performance (Warthen and Provencio 2012; P.R. Boyce 2014; Hanifin and Brainard 2007). The image forming route and non-image forming route in brain that effects human physiological and psychological well-being are shown in Figure 1.2. The green path refers to visual effects such as vision, perception and information which are mostly managed by brain. This process is related to human physiology. However, the blue path travels through the retinohypothalamic pathway to the spinal cord and superior cervical ganglion. These route indicates the non-image forming photoreception which is associated with human psychology, i.e., mental wellbeing, physiological arousal and performance (Smolders 2013; Licht and Wissen 2014). The detail of these processes will be explained in further sections.

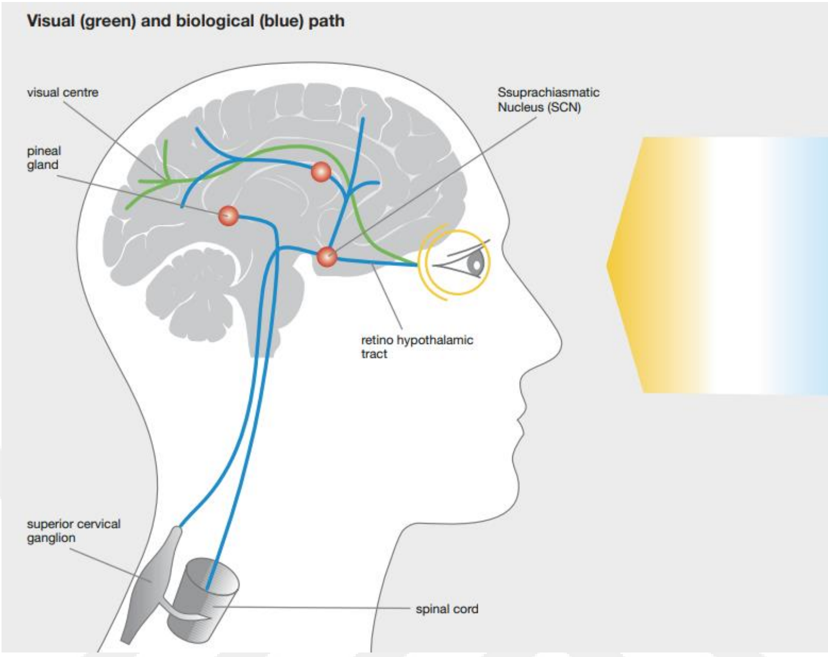


Figure 1.2. Image-forming (green) and non-image forming (blue) paths that followed by light coming into the eye (Source: Licht and Wissen 2014)

2.1.1. Visual Effects of Light (Image forming path of the light)

Image-forming photoreception begins when light entering the eye activates rods and cones, which are light-sensitive cells in the outer layer of the retina that are primarily concerned with vision. Light-detecting rods and cones transmit this photic information to the visual cortex via the primary optic track. The visual cortex is the part of the brain that processes visual information, and in this way we can visually perceive the forms and colours of objects around us, describe our position and direction, and interact with our environment (P.R. Boyce 2014; van Bommel and van den Beld 2004).

While rods are related to twilight vision, cones make it possible to see colours and fine details under sufficient lighting levels. If the lighting is not sufficient, neither objects can be recognized nor colours can be distinguished. According to spectral sensitivity, cone receptors are divided into 3 as S-cones, M-cones and L-cones. S-cones are most sensitive to light in the short wavelength region, while M-cones in medium wavelength and L-cones in the long wavelength region. Since daylight is consisting of a wide range of wavelengths, mostly cones are concerned with the vision in the daytime (P.R. Boyce 2014; Mark Stanley Rea 2000; van Bommel and van den Beld 2004).

The visual system allows to create a virtual model within the brain regarding the physical environment we are in. This model guides people in space, allows them to perform various visual tasks, but can be perceived differently by each person. For example, one person may find the environment spacious or pleasant, while the other does not. Thus, the model in the brain formed by visual system affects human functioning through both visual performance and visual experience (Cuttle 2008).

Visual Performance: Visual performance indicates the ability to perceive and process the visual environment accurately in order to perform visual tasks. Previous studies show that visual performance depends on lighting conditions as well as factors such as task characteristics, age, and so on. The thresholds for visual acuity, brightness, contrast, colors depend on lighting conditions and these factors play a significant role in the accurate and rapid perception of visual information (P.R. Boyce 2014; Mark Stanley Rea 2000). For example, in the study conducted by Rea and Ouellette (1991), it has been observed that while the visual performance is constant over a wide range of luminance levels and luminance contrasts, when it gets below a certain point, it worsens the capability to perform the task over time and therefore the motivation to perform the task, depending on the visual discomfort. Accurate and fast detection of the relevant visual task components is essential for many daily tasks and underlines the relationship between visual performance and human functioning (Mark S. Rea and Ouellette 1991).

Lighting conditions do not only enable vision by simply providing adequate light to perform visual tasks but also affect visual comfort. Excessive or insufficient light levels, high luminance ratios, flicker, or inappropriate light angle in visual environment may cause visual discomfort. Visual discomfort can prevent us from perceiving and processing the visual information properly and can negatively affect visual performance. Improper lighting conditions deteriorate the mental well-being and health of people; it may lead people to get tired easily, cause symptoms such as headache and eye pain, and thus reduce their task performance. Therefore, the purpose of good lighting should be to provide sufficient light to perform visual tasks by avoiding factors that may cause visual discomfort. The close relationship between visual performance and visual comfort has been the subject of many studies and lighting requirements have been determined for optimum visual task performance and visual comfort. These requirements will be explained in the following sections (P.R. Boyce 2014; Mark Stanley Rea 2000).

Visual Experience: The majority of studies focus on the effects of light on visual performance and visual comfort, but ignore how people experience and react to the visual environment. Effects of light on experimental aspects refer to individuals’ impressions about the space, their expectations, attention to specific objects or pleasantness of lighting in an environment. This visual experience, namely subjective evaluations, is also possible owing to image-forming photoreception in the brain. The perceived objects through the light in the environment are not just an image created on the retina, it also includes the individual's evaluations and expectations regarding the perceived object (Veitch, Stokkermans, and Newsham 2013; Veitch et al. 2008).

Numerous studies have been carried out in order to reveal how different light settings affect the room atmosphere and therefore the appraisals of the people. For example, Flynn et al. (1973) investigated whether variations in light arrangements have an impact on subjective impressions of people in a conference room and on individual's behaviour in a restaurant. It has been demonstrated that lighting conditions can create common impressions of a space and lead to behavioural preferences among different people. Another study concluding that light settings can lead shared impressions showed that people in a room with higher illuminance often perceive the environment as brighter, and lighting with low correlation colour temperature (CCT) gives people the feeling that the environment is less tense, more relaxing and calm (Flynn et al. 1973).

In a study, Kruithof (1941) investigated how light settings affect the subjective assessment of individuals, depending on different illuminance levels and colour temperatures. A total of 25 combinations consisting of 5 illuminance levels and 5 colour temperatures were examined using RGB fluorescent lamps with dimmers. As a result of subjective experiments using scale models, preferred lighting and colour temperature combinations under various everyday activities were obtained. According to Kruithof curve, lower lighting levels are preferred at lower CCT levels, while higher illuminance levels perceived as more pleasant at high CCT levels. In addition, subjective evaluations varied according to the intensity level of the lighting settings: while the environment is defined as dim and cold below a certain illuminance level, it is stated that the colours in the environment are perceived as unnatural for the illuminance values above. Although the Kruithof curve represents the common perception and experience, it is not possible to define the optimum light settings in terms of pleasantness and individuals' preferences (Kruithof 1941).

A series of empirical studies conducted by Veitch et al. (2008, 2013) and significant results have been obtained related to influence of light on the mood, health and performance of office workers. These studies revealed that the lighting conditions experienced in the office environment have an effect on the mood, motivation and satisfaction of the employees (Veitch et al. 2008; Veitch, Stokkermans, and Newsham 2013). In addition, it has been stated that the actual affectional and cognitive functioning of employees may vary according to their beliefs and expectations. Beliefs and expectations refer to individuals' assumptions regarding the potential effects of light. For instance, if the lighting conditions of the environment do not match the expectations of the person, it can be evaluated as unsatisfying or inappropriate and may negatively affect the task performance. People prefer areas daylit work environments instead of artificial lighting, as the movements and changes in light levels during the day are thought to be beneficial for mental wellbeing, performance and health (Galasiu and Veitch 2006; Veitch and Gifford 1996).

2.1.2. Biological Effects of Light (Non-Image Forming Path)

Recent studies discovered that the light coming to the retina is not processed only by rods and cones, but also by third photoreceptor named " intrinsically photosensitive Retinal Ganglion cell (ipRGc)" (Berson, Dunn, and Takao 2002; Hattar et al. 2002). These photosensitive ganglion cells contain melanopsin, which is the most sensitive photopigment to short-wavelength radiation. Short-wavelength radiations are known to induce various physiological responses in neuroendocrine and neurobiological systems, such as setting the body clock, regulating hormones, and maintaining alertness. These receptors detect non-visual light information and transmit it via the retinohypothalamic tract to the Suprachiasmatic Nucleus (SCN) in the hypothalamus, activating the circadian system. The information is also sent from the SCN to the pineal gland where it is used for hormone production and regulation of body temperature. This pathway of the light in the brain, which affects the mental and physical health, mood and performance of people, is called non-image forming photoreception (Gooley et al. 2003; Lucas et al. 2012; Hattar et al. 2002). Studies on the non-image forming photoreception have been mainly carried out in chronobiology and neuroscience laboratories, focusing on the behavioural and physiological effects of light entering the human eye, such as regulation of circadian rhythms, hormone secretion, core body temperature and brain activity. However, these studies of human physiology also demonstrate the significance of light exposure for attention and sleepiness of individuals in their task performance (Cajochen 2007; Chellappa, Gordijn, and Cajochen 2011; Hanifin and Brainard 2007). Therefore, the non-image forming effects of light are investigated in two groups as direct (non-circadian) effects and circadian effects according to the instantaneous or temporal changes in human behaviour and physiology.

Circadian Effects of Light: Circadian rhythms refer to the approximately 24-hour cycles that can be found in human beings, plants, animals. It consists of regularly recurring biological incidences such as sleep and waking phases, feeding pattern, hormone production and brain activity (Van Dongen and Dinges 2000; Schmidt et al. 2007). The Suprachiasmatic Nucleus (SCN) in the hypothalamus is the part of the brain responsible for circadian rhythm, where cells are synchronized with the daily light-dark cycle based on environmental time. If the internal clock and natural rhythm do not match, people may feel tired, sleepy, or distracted. In other words, the circadian rhythm determines whether we are sleepy, active or vigilant at work places (Martine Knoop 2006).

Light is an essential component of circadian rhythm: it functions as a time cue by affecting the main clock, the SCN, and regulates the rhythms in different body components accordingly (Cajochen 2007). Thus, it is ensured that metabolic activities such as hormone secretion, regulation of body temperature and blood pressure in the human body occur in certain periods (Czeisler and Wright 1999). In the morning, human body begins its active cycle depending on the sunrise and increasing light levels, and a number of hormones such as cortisol, serotonin and adrenaline begin to be produced. During this time, cortisol, a stress hormone, functions like a biological alarm system and stimulates the body. Increasing cortisol level prepares the body and mind for the daily activities. Among the others, cortisol raises blood sugar that energizes the body and strengthens the immune system. At this stage, it is also ensured that sufficient level of serotonin is secreted through the pituitary gland. Serotonin plays an important role in individuals' psychological processes. It ensures a high level of motivation and mood during the day. It also assists cortisol hormone when it is not produced enough in the daytime. While the production of adrenaline and serotonin continues throughout the day, cortisol only becomes active in the system for a short time and decreases over time (Czeisler and Wright 1999; Duffy and Czeisler 2009; Kreitzman and Foster 2011).

Another hormone that is an integral part of the circadian rhythm is melatonin. Also known as the sleep hormone, melatonin works in the opposite direction of the cortisol cycle. As the light intensity decreases towards the evening (sunset), the melatonin level increases and is produced during the night. For human beings, this is a cue for nighttime, so that melatonin reduces the body activity, slows down the metabolism and prepares body for sleep. During this phase, many other metabolic processes such as blood pressure, body temperature, hormone production also slow down. The body ensures the regeneration and repair of cells by secreting growth hormone. In the morning, melatonin secretion decreases, cortisol production increases, and this cycle continues every 24 hours (Chellappa et al. 2011; Lewy et al. 1980). Figure 1.3 shows the behavior of basic components that play a role in circadian rhythm such as body temperature, melatonin, cortisol, and alertness over a period of 2x24 hours.

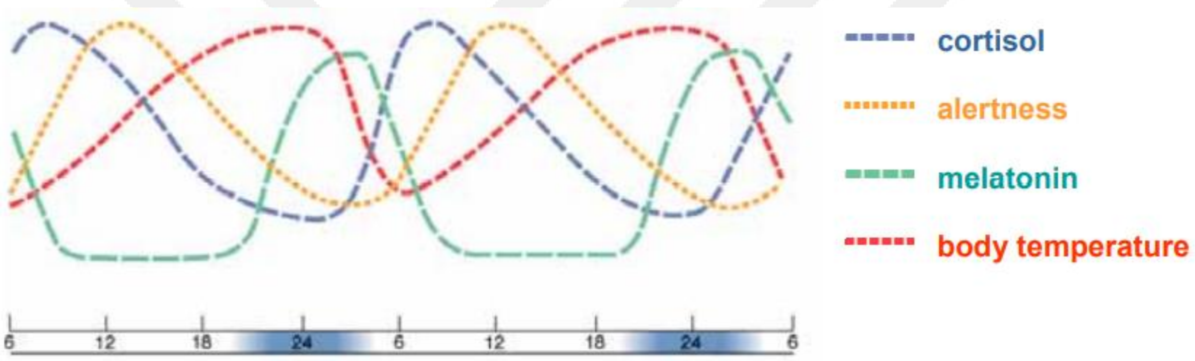


Figure 1.3. Hormone production, body temperature and alertness over time during the day (Source: Martine Knoop 2006)

The human internal clock needs to be readjusted every day to synchronize with environmental time, and light is a significant time cue (also called Zeitgeber) for this synchronization (Arendt and Broadway 1987). When there is a phase shift between our biological clock and the daily light-dark cycle, human health is adversely affected in physiological and psychological aspects. A mismatch can occur between the internal rhythms of not only SCN but also different body components (such as lungs, heart, liver, muscles, etc.) and this is called internal desynchronization (RG Foster 2010; Kreitzman and Foster 2011). This situation triggers several disorders such as daytime sleepiness, nighttime insomnia, irritability, mild depression, gastrointestinal distress, and so on. It also negatively affects cognitive abilities like memory deterioration, confusion, increasing error rate in workplaces (Waterhouse et al. 2007). People who work night shifts or travel over several time zones (jet lag) are typical examples of situations where the circadian rhythm is disrupted. People in night shifts try to keep themselves in the daytime rhythm, although the biological clock wants to be asleep at night. Therefore, these people are faced with undesirable situations such as lack of focus and attention, excessive sleepiness and accident risk in the early morning and late at night (Dijk and Lockley 2002; Czeisler and Wright 1999). Studies show that these phase shifting effects of light, i.e. non-visual effects, depend on the duration and timing of light exposure, light wavelength and spectral distribution, light intensity (Czeisler and Gooley 2007; Martine Knoop 2006). These insights are particularly relevant to the longer-term effects of light on the regulation of physiological and psychological processes (e.g. hormone production, sleeping pattern, vigilance, mood). However, light can also lead direct (acute) changes on human physiology, experiences and behavior.

Direct, Non-Circadian Effects of Light: Regardless of circadian rhythm, direct effects of light can occur at any time, day or night, by exposure to bright light (Martine Knoop 2006). Multiple studies carried out to investigate potential physiological and psychological effects of bright light exposure during the daytime and nighttime. In the study conducted by Rüger et al. (2006), it has been shown that exposure to high light levels at night causes a sudden decrease in melatonin secretion and reduction of sleepiness. It has also been revealed by physiological measurements that nocturnal exposure to bright light can increase heart rate and core body temperature and regulate brain activity. Besides physiological arousal, it was observed that subjective alertness increased and attention and cognitive task performance improved (Ruger et al. 2006).

Lockley et al. (2006) examined the direct effects of light on alertness, performance, and waking electroencephalogram in terms of the spectral composition of light. Frequency-specific changes in awake EEG demonstrated that short-wavelength light instantly mitigates the negative effects of circadian impulses for sleep on alertness, performance, and ability to maintain attention. Subjects exposed to monochromatic blue light (460-nm light) at night for 6.5 hours had significantly lower subjective sleepiness rates, faster auditory reaction, and less failure due to inattention than those exposed to 555 nm light (Lockley et al. 2006). In a similar study by Kayumov et al. (2005), it was found that the lack of blue light as a result of wearing glasses that block wavelengths less than 530 nm does not suppress melatonin at night as with white light at the same illuminance level (800 lux) (Kayumov et al. 2005). Another study, which evaluated by self-reported alertness, heart rate, melatonin suppression, and core body temperature, also revealed that the direct activating effects of nighttime light exposure were highly sensitive to short-wavelength light (Cajochen et al. 2005).

Chellappa and colleagues (2011) investigated how light sources with different color temperatures affect human alertness and cognitive performance. Sixteen healthy young men were exposed to light sources with a color temperature of 6500K, 3000K and 2500K for 2 hours in the evening. The results show that exposure to light at 6500K resulted in greater melatonin suppression, along with improved subjective alertness, visual comfort and well-being. Regarding cognitive performance, higher CCT levels led to significantly faster response times in tasks related to sustained attention (Chellappa et al. 2011). Similarly, Wood et al. (2013) stated that 2 hours of nocturnal exposure to self-luminous tablets viewed with the blue light can result in significant suppression of melatonin. Study also pointed out that the duration of blue light exposure is also important for human circadian rhythm (Wood et al. 2013).

Leproult et al. (2001) reported that the transition from low light intensity to high light intensity in the early morning suppressed melatonin secretion and caused a sudden increase in cortisol levels. However, bright light in the afternoon had no impact on hormonal or behavioral parameters (Leproult et al. 2001).

Thus, many studies have shown that light can be used to reduce daytime and nighttime sleepiness, increase sustained attention and visual acuity by causing acute activating effects for the human body. These non-circadian, direct effects are most effective under high light levels and blue-spectrum light conditions. In the light of all this information about the visual and non-visual effects of light on human beings, in the next section, appropriate lighting conditions for workplaces will be examined.

2.2. Parameters Affecting Lighting Quality in Workplaces

The standard approach to lighting mostly focused on providing adequate light as an essential element to enable vision to fulfill tasks. However, in order to talk about the lighting quality in the environment, both visual and psychological comfort should be provided. According to a behavioral-based definition of lighting quality, the luminous environment supports a number of requirements for those who will experience the space (Veitch and Newsham 1996):

- Visual acuity
- Improving task performance
- Supporting communication and interaction
- Having a positive effect on mood (happiness, alertness, pleasantness...)
- Providing good conditions for health and safety
- Contributing to the aesthetic appreciation of the space

Among these listed aspects, visual acuity, task performance and ensuring health and safety point out the physical parameters that should be achieved for good lighting quality, while contributing to communication, mood and aesthetics appraisal indicate psychological parameters. The fact that lighting also concerns the use of energy and the economy in buildings has resulted in the vast majority of research considering lighting for offices, and relatively fewer studies in other settings (Licht and Wissen 2014). Today, various lighting standards developed particularly with reference to workplaces to determine lighting conditions are based solely on empirical evidences. For example, the EN 12464-1 standard suggests that the indoor lighting quality can be evaluated with lighting level, brightness distribution, glare limitation, potential reflections, color temperature, and color rendering (EN 12464-1, 2011). Although the limitations for these quantitative evaluation of light differ according to the standards, they constitute the fundamental elements in the traditional lighting design approach. Still, these standards can be useful for determining the size and position of lighting systems to provide the average illuminance required for different work activities. In addition to lighting standards, with the developing technology, various new features such as, energy efficiency, daylight integration, personal control, being an interior design element are considered as lighting quality criteria (Licht and Wissen 2014).

The psychological effects of lighting depend on user behavior and experience, and therefore cannot be decided in advance with definite judgments. However, the number of studies on user behaviors and experiences has been increasing in recent years and user preferences are being investigated for a better quality of lighting. Features that will define the quality of a lighting installation in workplaces according to DIN EN 12464-1 standard are given in Figure 1.4 as a diagram.

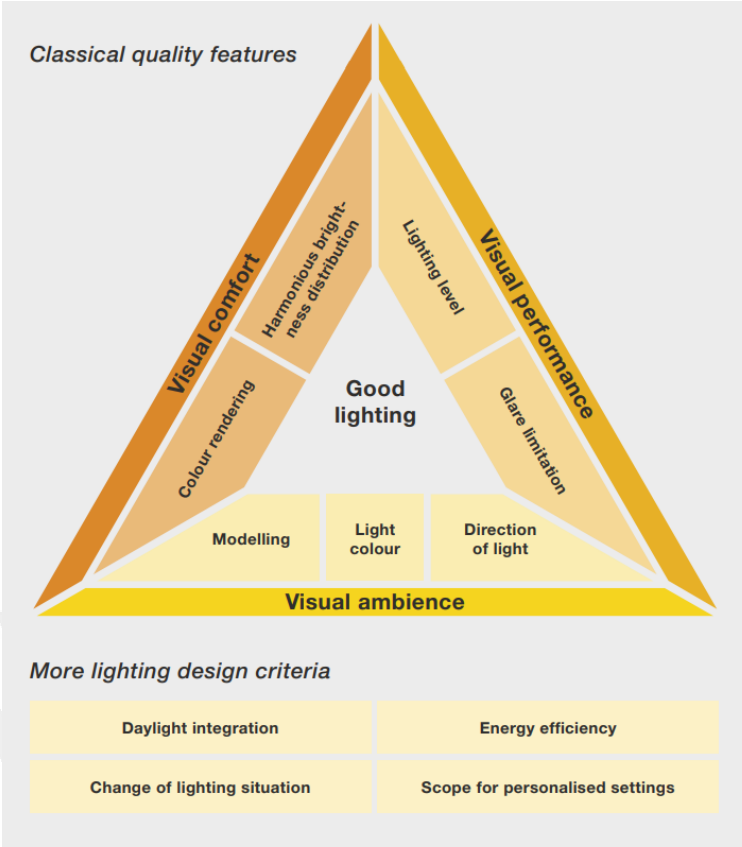


Figure 1.4. Interior lighting quality criteria altogether (Source: Licht and Wissen 2014)

2.2.1. The Physical Aspects of Visual Comfort

The appropriate and sufficient lighting for the related task enables people to perform their visual tasks efficiently and accurately. According to lighting standards, lighting conditions should meet the following three basic human needs (EN 12464-1, 2011):

- Visual comfort - indicates well-being, indirectly contributes to the increase of work performance and work quality.
- Visual performance – point out the ability to perform visual tasks for a long time without getting tired easily
- Safety – refers to protecting human health

Technological advances in the science of photometry and illumination engineering made lighting identifiable and measurable. Luminous flux is radiant flux evaluated according to the CIE (International Commission on Illumination) Relative Photopic Response. It is also known as the V (λ) function, where V refers to the relative human sensation of brightness with respect to the wavelength of the radiant flux λ (lambda) (Figure 1.5). It indicates the visual response adapted to light, often used for architectural lighting (Licht and Wissen 2014).

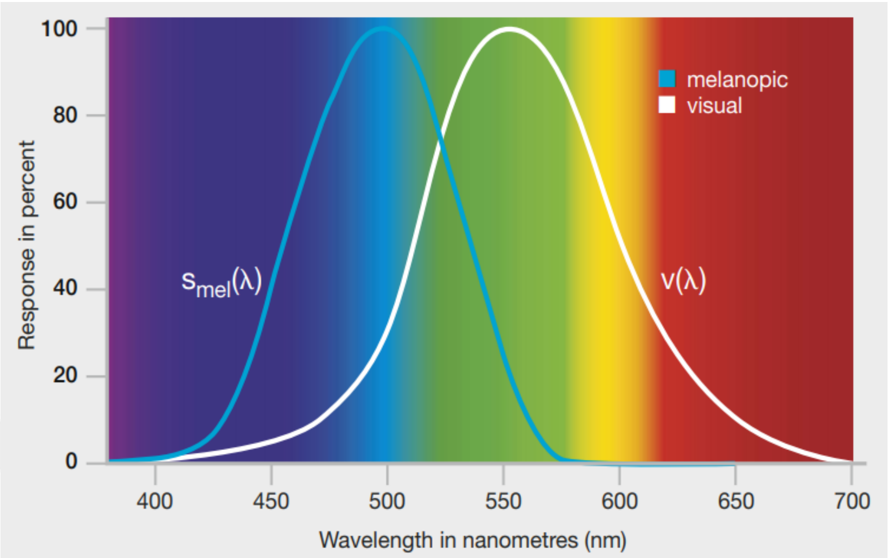


Figure 1.5. The CIE relative photopic response V(λ) function and action spectrum of melatonin suppression Smel (λ) during the day (Source: Licht and Wissen 2014)

Luminous flux refers to “the total amount of radiant energy emitted from a light source per unit of time” and measured in lumens. Luminous intensity, on the other hand, is “the luminous flux emitted per unit solid angle by a light source”. The unit of light intensity is Candela. Illuminance (E) is the density of the luminous flux that corresponds to a point on a surface. It is measured in lux and equals one lumen per square meter. Luminance (L) is the main lighting parameter perceived by the eye and is used to describe the physical amount of light reaching the eye from the surface. Reflectance (ρ) is defined as “the percentage of incident light that is reflected from a surface, with the remainder absorbed, transmitted, or both” (Cuttle 2008). These are the basic terms of lighting that allow the measurement and definition of lighting conditions. The summary of expressions is given in Table 1.1. These photometric parameters, together with environmental information, are essential elements of lighting standards established to define conditions regarding good lighting quality.

Table 1.1. Fundamental elements in a standard lighting design approach (Source: Bellia, Bisegna, and Spada 2011)

Parameter	Formulation	Unit
Luminous flux, Φ_v	$\int_{380}^{780} \frac{d\Phi_e(\lambda)}{d\lambda} K(\lambda)\, d\lambda$	[lm]
Luminous intensity, I	$\frac{d\Phi_v}{d\omega}$	[cd]
Illuminance, E	$\frac{d\Phi_v}{dA}$	[lx]
Luminance, L	$\frac{dI}{dA\ \cos\alpha}$	[cd/m^2]
Reflectance, r	$\frac{\Phi_r}{\Phi_i}$	[−]

Main quantitative parameters determining the lighting quality of environment are illuminance level, luminance distribution, glare, color rendering and color appearance of the light. Regulations and recommendations for these parameters associated with lighting conditions are determined according to specific tasks (EN 12464-1, 2011).

Illuminance: The amount and distribution of illuminance in the task area and its surroundings play a significant role in the individuals' ability to perform visual tasks accurately, quickly and comfortably. The minimum average illuminance level required for each task is given in Table 2. These values are determined by taking into account factors such as visual comfort and well-being, difficulty of the task, visual ergonomics, contribution to safety of the activity and economy.

Luminance Distribution: The distribution of luminance in the visual environment supports the adaptation of eyes to the illuminated area, providing better task visibility and clarity. A balanced distribution of brightness improves visual acuity, visual comfort, contrast sensitivity, accommodational functions and eye health. On the other hand, when there are vast differences in brightness, eye strain occurs due to high luminance contrast. High luminance values can cause glare, whereas low luminance levels create a dim and unstimulating work environment. Achieving a well-balanced luminance distribution in a space involves considering luminance values on all reflective surfaces, which depend on both reflection and illuminance. It is recommended to have bright interior surfaces, especially on the walls and ceiling, in order to avoid the gloomy environment and to increase the visual adaptation and comfort (EN 12464-1, 2011). The uniformity ratio is used to understand how evenly light is distributed on a certain plane. It simply refers to the ratio of the minimum illumination level to the average illumination level in a given area. The recommended minimum uniformity values in workplaces to avoid distraction and visual discomfort are given in Table 2.

Glare: Glare is the bright areas within the field of vision that impacts our visual perception. It negatively affects our ability to see and causes discomfort. Therefore, glare should be limited to prevent possible errors, fatigue and accidents. Glare can occur in two ways as a discomfort glare or disability glare. Disability glare is caused by extremely bright areas in the field of view that produce scattering of light inside human eye. It substantially reduces vision by disrupting visual contrast. Direct incoming light or specular reflections of the sun in an office environment can be given as an example. The discomfort glare does not have a certain impairing effect as in the disability glare, but it can be disturbing and distracting. It usually described as the inconvenience caused by bright light sources, lighting fixtures, windows or other shiny surfaces. Disability glare is not the main concern in indoor lighting environment if discomfort glare limitations are addressed. The discomfort glare arised directly from the installation of indoor lighting fixtures can be determined by the CIE Unified Glare Rating (UGR) method. The recommended quantitative limiting values for discomfort glare are given in the Table 2.

Color Appearance: Color Appearance refers to visible color (chromaticity) of the emitted light from the light source. Correlated color temperature (CCT) is the quantitative representation of the color appearance and expressed in kelvin (K). Low correlated color temperatures (below 3 300 K) indicates warm color while high correlated color temperatures (above 5300K) presents cold color appearance. For instance, color characteristics of daylight vary throughout the day. The light is warm in color appearance at sunrise and sunset, while cool white light is dominant at noon. Light and color also have an impact on psychology, mood, aesthetics judgements and the naturality of the appearance.

Color Rendering: In order to achieve a better visual comfort, performance and well-being, lighting conditions should be created in such an accurate way that the surrounding colors and objects as well as the human skin tone look natural and healthy. The color rendering index (Ra) is used to quantitatively define how closely a light source presents the surrounding objects to their original color. The highest value of the color rendering index is 100, that is, values closer to 100 means more natural color appearance. Recommended minimum Ra values for different task areas and activities are presented in Table 1.2.

Table 1.2. Recommended illuminance, uniformity, glare rating and color rendering values for various tasks and activities in workplaces (Source: EN 12464-1, 2011)

Ref. no.	**Type of area, task or activity**	E_m **Ix**	UGR_L -	U_o -	R_a -	**Specific requirements**
5.26.1	Filing, copying, etc.	300	19	0.40	80	
5.26.2	Writing, typing, reading, data processing	500	19	0.60	80	DSE-work, see 4.9.
5.26.3	Technical drawing	750	16	0.70	80	
5.26.4	CAD work stations	500	19	0.60	80	DSE-work, see 4.9.
5.26.5	Conference and meeting rooms	500	19	0.60	80	Lighting should be controllable.
5.26.6	Reception desk	300	22	0.60	80	
5.26.7	Archives	200	25	0.40	80	

2.2.2. The Psychological Aspects of Visual Comfort

In addition to physical comfort conditions, providing psychological comfort conditions is also highly important in terms of mood, work performance, productivity and satisfaction of people. It is known that psychological comfort is directly related to the lighting preferences of the people. The psychological aspects of visual comfort can be examined under the headings of vision and perception, mood, and performance.

Vision and Perception: The perception of space becomes subjective with elements such as light, texture, sound and smell. With all of these subjective elements, the light, shadow, color of the space, smell and the texture of the surfaces are felt, perceived with their meanings and evaluated with the personal taste criterion (Gezer 2012). Elements/objects in the space exist by means of light. Therefore, users' perception of the space may vary depending on the lighting used in the space. The characteristic of light in a space plays a significant role in subjective evaluations such as spaciousness, comfort, visual clarity and satisfaction, and the degree of detail perception (Özkum 2011).

Windows allow daylight into the interiors as well as provide view to the outside. This has a direct effect on improving the pleasantness of the environment, reducing stress and increasing productivity. The view from the window provides the connection with the outside world, the perception of the time of the day or the year, the knowledge of the weather conditions and the changes in the movements of the sun. Changes in light levels throughout the day provide mental relaxation and stimulation. People should be able to detect the time of day and weather conditions when they look out of the window. Windows that are inadequate in size, unclean, or with dark colored/coated glazing may cause claustrophobia and deteriorate well-being. The presence of windows and the penetration of daylight into the interiors are associated with an increase in satisfaction and productivity in the workplaces (Özkum 2011).

In the LEED (Leadership in Environmental and Energy Design) certification system, view to outside and daylighting conditions are included under the main heading of indoor physical environmental quality. It is the criterion that evaluates the users' ability to make visual contact with the external environment and to take daylight into the building. If daylight illuminance of 250 lux is provided in 75% of the regularly occupied areas, 1 point can be obtained from this section. Likewise, if 90% of the regularly occupied space are visible to perimeter glazing, 1 more point is obtained.

In BREEAM (Building Research Establishment Environmental Assessment Method), another certification system, 1 point can be obtained if daylight is provided in at least 80% of the the floor area except in circulation areas. Providing visual contact with the outdoors is also evaluated. According to this criterion, it should be ensured that every user establishes eye contact with the exterior environment in order to prevent eye fatigue and dullness, particularly in office buildings. It is required that the relevant areas are at a maximum distance of 7m from the window providing outside view and that the minimum 20% of transmittance of windows should be provided. If the specified criteria are met, 1 point can be obtained.

Mood: The personal characteristics of the users have an effect on the lighting preferences of the place. Factors such as a person's age, gender, and health problems can determine their lighting preferences. Light not only provides a perceptual view, but also enables people to have different cognitive, emotional, and behavioral responses throughout the day (Özkum 2011).

During the winter, people may feel more tense, unhappy, less motivated and slower in reactions. This situation is the psychological effect of the winter season due to low light levels. Some people may be severely affected by this condition and experience a clinical depression. This condition is named Seasonal Affective Disorder (SAD) and expressed as a depression due to lack of sunlight. SAD is common in people living in northern latitude. It is known that women suffer from this syndrome more frequently because they are more sensitive to light than men. It shows symptoms such as fatigue, irritability, unhappiness and distraction at school in children. In order to overcome this situation, "light therapy" is applied to individuals at high illuminance levels in varying periods. Light therapy applied early in the morning is effective in overcoming the symptoms of depression that occur due to seasonal changes and lack of daylight (Brandi 2012; Şahin 2013).

Color temperature and color appearance of light also have various effects on human psychology. While warm colors have a relaxing effect on people, cold colors can create a feeling of spaciousness. The color of the light source can be used to add different features to the space and create an attractive atmosphere. In the lighting design decisions, the psychological effects of light on people should be taken into consideration as well as the physical properties of the environment (Şahin 2013; Özkum 2011).

Performance: Work performance can be defined as the ability of individuals to meet the parameters required by their tasks, such as problem solving, communication with colleagues, teamwork performance and productivity level (Silvester and Konstantinou 2010). Work performance depends on internal and external environmental conditions such as lighting and ventilation as well as individual parameters such as employee motivation and well-being. The lighting conditions of the environment play a role on the work performance by affecting the visual system, perceptual system and circadian system. Lighting conditions parameters affecting the working performance can be counted as lighting according to the task type, illuminance level, color temperature, and luminance difference and so on. Lighting design considering the visual and non-visual effects of light on people has positive contributions to improvement of work performance, increase in accuracy and productivity, decrease in error rate in visual tasks, and well-being/satisfaction of employees. On the other hand, poor lighting practices negatively affect work performance by leading to a fatigue (easier than it should be), distraction, nervousness and deterioration of the optic nerve (Silvester and Konstantinou 2010).

The current standards and recommendations, particularly for office environments and classroom lighting conditions, are based on findings associated with ergonomic needs of visual tasks. However, lighting conditions - although not yet included in current lighting standards - may affect work performance, health and well-being in ways other than visual performance. Studies investigating visual performance mostly focused on the physical environment and visual tasks. However, many work-related tasks involve a laborious and complex process that includes both vision and cognitive skills, attention, and motivation. The traditional lighting design approach alone may not adequately address the 'non-visual' effects of light or ensure optimal visual comfort and performance. Research has shown that the non-visual (circadian) effects of light are influenced by factors such as light intensity, spectrum, and timing of exposure (Bellia, Bisegna, and Spada 2011). Therefore, in order to better understand and evaluate lighting conditions in terms of comfort and performance, and to ensure that the biological effects of light on humans are taken into account in the application of lighting design, other luminous properties such as luminosity in the eye and spectral power distribution of the light at eye-level should also be considered (Bellia, Bisegna, and Spada 2011; Smolders 2013).

2.3. Human Centric Lighting Design Concept

Daylight, which has physiological and psychological effects on human metabolism, is dynamic, varying in aspects like colour temperature, light intensity, and colour throughout the day based on the sun's position. These changes in daylight affect the circadian rhythm and therefore, daylight is crucial for human life.

In the past, people spent the majority of their time outdoors in natural daylight. Nowadays, most of their time is spent indoors in environments lit by artificial light sources such as homes, offices, hospitals, and schools. The human circadian rhythm and internal biological clock are aligned with the Earth's light-dark cycle. Therefore, irregularities may occur in human circadian rhythms depending on the light that they are exposed to indoors. The concept of 'human-centric lighting' emerged to bring the dynamic qualities of sunlight into living and working spaces, aiming to maintain the biological clock and circadian rhythms. Human-centric lighting is the set of technical methods used to obtain the biological effects of daylight in an artificial lighting environment (Houser and Esposito 2021). That is, lighting is designed to balance the human day/night rhythm. With human- centric lighting systems, it is aimed to obtain artificial light in natural light quality and to ensure that human metabolism reacts in artificial lighting conditions as in day-lit environment. The human-centric lighting concept focuses on developing and using lighting systems that support well-being, mood and health rather than an aesthetic perspective (Köseli 2018; Kompier, Smolders, and de Kort 2020).

Human-centric lighting systems are used particularly in areas where daylight is not available. With these systems, dynamic lighting designs can be made by modelling and predicting variations in parameters such as light intensity, illuminance and colour temperature for different times of the day. In the design process, technologies such as smart lighting systems, sensor technologies, advanced light management systems, artificial intelligence applications, wireless control systems and IOT can be used (Şahin 2013; Memiş 2019).

The concept of human-centric lighting seeks an answer to the question of what is the relationship between the human emotional state, performance, biological rhythm during the day and the light-dark rhythm of the world. With human-centric lighting applications, it is aimed to balance the visual, emotional and biological benefits of light for people. Light is a significant environmental factor in achieving and maintaining this balance. Daylight serves as the benchmark for optimal light quality and forms the foundation of human-centric lighting (Figueiro et al. 2019; Kompier, Smolders, and de Kort 2020).

Human- centric lighting is associated with the non-visual effects of light on human metabolism and its effects on the circadian rhythm. Light affects the visual, non-visual and psychological system. In the diagram in Figure 1.6, the effects of the parameters such as amount, spectrum, distribution, timing and duration of the exposed light on visual and non-visual systems, thus on the psychological system are shown. In recent years, researches and experiments on the non-visual effects of light by researchers and lighting companies and the resulting scientific outputs have contributed to the development of human-centric lighting method.

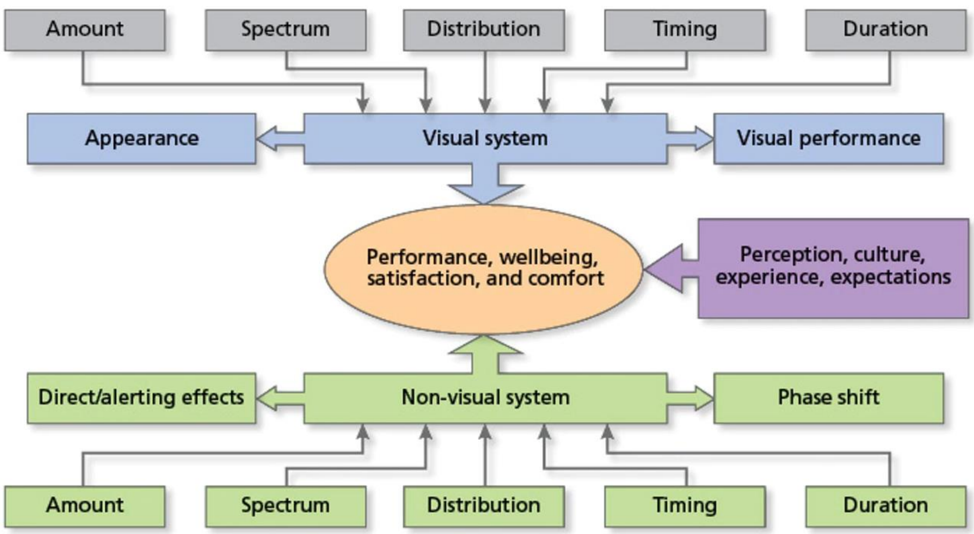


Figure 1.6. Parameters of light affecting the human visual and non-visual system (Source: Memiş 2019)

2.3.1. Current Studies Investigating the Effects of Light on Human

It is known that the effective use of daylight in buildings increases the visual performance of the occupants, reduces the electrical energy demand for interior lighting, and minimize the cooling loads of the building by decreasing the use of artificial light sources and using the shading elements (Peter Boyce, Hunter, and Howlett 2003; Ihm, Nemri, and Krarti 2009; Konis 2013). The benefit of natural lighting is not limited to energy consumption and providing comfort conditions, but it is often emphasized in recent researches that it also affects human health (psychology, eye health, hormone secretion, sleep/wake pattern, behaviors), working performance, students' learning ability, aesthetic judgements of building users and the perception of the physical environment (Andersen, Mardaljevic, and Lockley 2012; Bellia, Pedace, and Barbato 2013). These effects occur when the visual, biological and mental benefits of light come together. These issues constitute the basis of the concept of "human-oriented lighting" in particular; people feeling alert or non-stimulating; improving cognitive performances and emotional (mental) states; supporting the sleep and wake cycles is the content of this concept (Cupkova et al. 2019).

Although the use of daylight is increased, artificial lighting systems are still needed. Daylight illuminance levels may fall below the desired level due to sky conditions and the design of large buildings. Artificial lighting is necessary when long working hours are planned during the day, especially in working places. In these environments, lighting systems containing LED light sources are often preferred as they offer energy efficient and economical solutions. Despite the high amount of light emitted, the energy consumption values of these lamps are considerably low compared to fluorescents. Lamp life is quite long and maintenance costs are low. Besides these advantages, LED light can have negative effects on human health. These effects include issues such as glare, optical damage, LED flicker, nocturnal exposure to LED light, toxic chemical content of LEDs in detail (Ticleanu and Littlefair 2015). It is known that the energy distribution of the LED light spectrum is higher in the blue wavelength. It has been discussed in recent studies that this may have an effect on the melatonin hormone suppression due to the circadian rhythm. The indicator that expresses this 24-hour cycle (circadian rhythm) is calculated by the percentage of melatonin hormone secretion, in other words the ratio of "circadian stimulus - CS". CL can be calculated with a set of formulas developed with multiple field measurements, depending on the spectral structure of a light source, e.g., LED light or daylight (M. S. Rea et al. 2010). In classrooms and offices; color temperature, illuminance level, spectrum of the light source and circadian rhythm have been associated with the learning performance of students and the work performance, by developing of various methods (Bellia, Pedace, and Barbato 2013; Gentile et al. 2018). These studies have gained importance in recent years and the number of researches in this field has been increasing. The most appropriate and accurate methods are being investigated.

The effect of indoor lighting conditions on productivity/learning, mood and human health has been studied by several researchers. In this context, the spectrum of daylight was discussed in a research. Several types of glass types and colors of interior surface materials were applied on the scale model, and then their effects on the interior physical environment were investigated by means of lighting simulations. Spectrum measurements of light in indoor and outdoor environment were taken, the illuminance level was measured from horizontal and vertical points, and then the Melanopic illumination level was calculated. The potential of surface material colors to affect the circadian rhythm is higher than glass types (Potočnik et al. 2019). In another study, the color of the window glass was examined and its effect on the daylight quality, attention/arousal, and the occupants' switch on/off pattern for electric light was examined. Glass types (variables) were applied on the scale model, and then a questionnaire was applied to participants. It has been determined that in case of using blue glass, the level of attention/arousal decreases. There was no significant difference in the switch on/off pattern of artificial lighting and it was considered that this might be related with the limitations of the chosen method. It has been observed that the daylight passing through the bronze glass causes a general tendency to pleasantness, and it has been concluded that this glass type enhances occupant's arousal/attention (Arsenault, Hébert, and Dubois 2012). The effect of window glasses on the color quality of daylight entering to the interior environment was discussed in another study. Laminated, monolithic, coated and applied film glazing types were tested. It is concluded that the possible increase or decrease in the color temperature and color rendering index depends on the type of material used to produce the glazing. It is known that the spectral transmittance values of the glass affect the color rendering index values of the indoor daylight. As a result of this study conducted in the laboratory, some of the standard color rendering criteria were not met. The authors suggested conducting studies on the quality of daylight in actual physical environments, including users (Dangol, Kruisselbrink, and Rosemann 2017). In a study conducted by Bellia et al. (2013) in a university classroom, it was found that not only the intensity of the light, but also the spectral power distribution (SPD) of light coming into the eye affects the circadian rhythm of the students and therefore plays a significant role in the arousal levels of the students. A study examining light transmittance considered three types of glass: spectrally neutral, a brightness-reducing solextra and a brightness-enhancing solar bronze glass. Glasses were applied on a 1:12 scale model of an office, and 25 participants were surveyed who observed the interior of the model and looked out at the real sky from the window of the model. It was stated that the minimum acceptable light transmittance of window glasses should be in the range of 25-38%. Such studies suggest that window glass types should be studied in the context of the non-visual effects of light on humans (Boyce et al. 1995).

Similar issues have been studied by considering the color temperature values (CCT) of LED lighting systems and their various effects on users together. Subjective evaluation methods were used in these studies. In a study (Zhu et al. 2017), cognitive performance, mood and alertness in work environments were tested according to CCT and illuminance level. Participants were less sleepy in bright light and the effect on long-term memory was mostly obtained in the cool light source. In another article (Knez 2001), the effect of light color on the short-term memory and problem solving of high school students (17-18 years) was investigated. It has been found that students perform better in a warm white light source, and that the blue light source impairs short-term memory and attention. In long-term memory, females performed better in artificial "daylight" white lighting than males, while males performed best in "warm" and "cool" white lighting. In a similar study by the same author (Knez and Kers 2000), positive effects were observed in both visual performance and cognitive and behavioral aspects of individuals with the enhancement of the lighting condition of the internal physical environment. Illuminance level is also an effective parameter. In another article (Choi and Suk 2016), the effect of color temperature on the performance and behavior of primary school students was examined. A classroom was created in the laboratory for physiological examinations, experiments were carried out for three different color temperature values of LED lighting (3500K, 5000K, 6500K), ECG (heart rate) was measured, math questions were asked for performance tests, control and experimental groups were formed, pretest and post-test was applied and statistical analysis was applied. Dynamic lighting systems have been discussed; color temperatures are grouped and suggested for 3500K easy, 5000K standard, 6500K intensive activities in learning environment. In the study of Gentile and collegues (2016), a classroom was experimentally investigated under fluorescent and LED lighting conditions. Questionnaires and tests were applied to the students, and cortisol (stress hormone) hormone levels were measured by collecting saliva samples. Accordingly, it has been observed that stress hormone secretion is reduced under daylight exposure. It is highly recommended that students exposed to daylight. In overcast sky conditions during winter, the LED lighting system better supported the cortisol suppression of the students compared to the fluorescent system (Gentile et al. 2018). In a study on the evaluation of the visual environment in terms of color temperature and light level in offices, low color temperature (CCT) values (2700 K - towards orange) provide relaxation, while higher CCT values (4000 K-towards blue) has been observed to give the space an impression of comfort and spaciousness (Manav 2007).

The effect of varying levels of daylight on visual and cognitive performance of people was discussed in a study (Leccese et al. 2019). Psychological and physiological factors have been associated with the working performance of VDT (visual display terminal) users. In order to examine the cognitive work performance on the computer screen, the letter search test (e.g. finding the orange T letter) was performed first, and the output was recorded in milliseconds. The next test is the Stroop test, which is about determining the color of the word that appears on the screen. For example, the word "red" is written in blue and the participant should notice the color of the writing as quickly and accurately as possible; the response speed is recorded. The attention/alertness of the participants was tested with the Karolinska Sleepiness Scale. Participants were also asked to evaluate their own task performances with visual analog scale (VAS). When the shading on, that is, the illuminance level was lower, their attention was higher in their color perception. Subjective performance differences were best observed in the morning hours. It has been proven that cognitive work performance increases when visual discomfort feelings are lower (Leccese et al. 2019).

2.4. Application of Artificial Intelligence Models in Lighting Design

Buildings should be designed to provide a sufficient level of illuminance in terms of energy-saving, user health, well-being, and visual comfort. For this purpose, several methods have been developed to estimate the lighting levels that can be achieved in a space during the initial design phase. These traditional methods, which are frequently used in lighting studies, are divided into three groups as physical modelling, computer simulations and mathematical formulas (Ayoub 2019).

In physical modeling, a scaled replica of the intended space is typically created, ranging from 1:8 to 1:32 scale, to forecast daylight levels at the actual site (Boccia and Zazzini, 2015). Various materials and objects with different reflections are included in the development of physical models to ensure proper reproduction of various real-life spaces. Although effective, this approach can be time-consuming and costly, particularly depending on the scale, building details (such as shading elements and outdoor components), and the necessity for repetition.

The use of computer simulations to predict lighting levels in buildings has been increasing in recent years. Various lighting simulation software are available on the market today. Although these software differs in terms of complexity, modelling and visualization ability, accuracy (in computation), etc., the computational methods they are based on (raytracing, radiosity, photon mapping) are generally the same (Ochoa, Aries, and Hensen 2012). These tools are advantageous in terms of offering speed and flexibility/repeatability in evaluating building lighting performance. However, it requires a difficult learning process for users and the accuracy of the results are highly dependent on the users' skills. Therefore, it is prone to errors due to the lack of experience of the person who generated the model.

There are also simplified mathematical formulas commonly used in the building industry to evaluate lighting performance. One of them is the Daylight Factor method, which is obtained by the ratio of the outdoor horizontal illuminance to the indoor horizontal illuminance on the workplane. The Daylight Factor still forms the basis of many building standards such as BS206-2 and BS 209-2011 (Boubekri 2004). While straightforward and easily implemented, this method does not account for critical factors such as climate, time of day, and sky conditions, which significantly impact the availability of daylight in a space. Daylight metrics such as Useful Daylight Illuminance and Daylight Autonomy have also been developed to address these shortcomings (Nabil and Mardaljevic 2006; Reinhart, Mardaljevic, and Rogers 2006). Nevertheless, relying on manual calculations for long-term assessments of lighting performance is often impractical. Furthermore, such analytical methods frequently lack a comprehensive evaluation of spatial lighting performance. For instance, these metrics may not indicate whether illuminance levels are uniformly distributed across the area(Zomorodian and Tahsildoost 2019).

Due to various shortcomings and difficulties in these three traditional methods, alternative methods have been researched in recent years and the application of artificial intelligence methods in building lighting performance evaluations has been studied. Artificial intelligence techniques utilize available data to identify patterns and relationships between causal and response variables. Once these patterns are learned, they can predict the response variable at a future time or under specific conditions (Jordan and Mitchell 2015). Artificial intelligence methods involve using computers to simulate human brain functions and behaviors, training them to learn human capabilities such as learning, judgment, and decision-making (Da

Xu, Lu, and Li 2021). It encompasses a knowledge-driven approach that treats knowledge as an object, acquiring, analyzing, and evaluating different methods of expressing knowledge. These approaches are used to simulate human intellectual activities (Duan and Da Xu 2012). The adaptive learning ability of artificial intelligence methods provides an advantage in solving complex, nonlinear problems that are difficult to solve analytically or numerically. Artificial intelligence integrates computer science with disciplines like logic, biology, psychology, and philosophy, achieving significant advancements in applications such as speech recognition, image processing, natural language processing, automatic theorem proving, and intelligent robotics (Rafiq, Bugmann, and Easterbrook 2001). Recently, it has been successfully applied in the field of building physics while calculating energy consumption in buildings or estimating daylight illuminance, etc.

In a study, artificial neural networks (ANN) method was applied to model the thermal behavior of various roof coverings used in buildings. To evaluate the roof coverings, test cells were built and the temperature in different parts of the cells was recorded. In addition to variables such as solar radiation, humidity and wind speed, the reflectivity and emissivity of the roof coverings were measured and used in the creation of the model. A statistical analysis based on computer simulations using artificial neural networks was carried out to analyse the parameters that most and least affect the heat flow in the roofs. It has been found that under certain conditions, small increases in the reflectivity value of the coating can cause significant changes in the heat flow through the roof (Ledesma et al. 2020). In another study, an extensive literature search was conducted on fuzzy hybrid techniques used in different civil engineering and management (CEM) applications (e.g. forecasting, decision making, optimization). It was stated that fuzzy hybrid techniques used in CEM could be beneficial in solving construction problems that could not be solved with standard techniques, and selection criteria were determined for the applications of fuzzy hybrid techniques according to different CEM problems (Nguyen and Fayek 2022). In a study examining the effect of vacuum PV glass on daylight performance and energy consumption (Qiu, Yi, Wang, and Yang 2020), a preprocessing coupling method is proposed. An artificial neural network (ANN) model was developed based on weather conditions and RADIANCE simulation results to predict indoor illuminance and office lighting energy consumption. It is concluded that the ANN model can predict the illuminance level with higher accuracy than the daylight calculation methods in EnergyPlus. It is stated that with the ANN daylight prediction model, the computational cost can also be significantly reduced compared to computer simulations. Ayoub (2020) comprehensively examines studies that use machine learning to quickly predict daylight performance in buildings according to their prediction scope, algorithms used, data sources and sizes, and evaluation metrics. Compared to complex simulations, machine learning algorithms have been proven to provide faster and more accurate predictions with low error rates in the studies examined. The author suggests increasing the use of such innovative computational methods in architectural practice, drawing attention to the knowledge gaps and missed opportunities in this field. In a similar study, the optimum machine learning algorithm was examined to evaluate daylight performance indoors. For this purpose, the performance of four different commonly used machine learning algorithms (random forest, generalized linear models, deep neural networks and gradient boosting models) was compared. It was concluded that deep neural networks are the most accurate and reliable algorithm with a rate of 0.99 (R^2) for estimating the daylight distribution (Ngarambe, Irakoze, Yun, and Kim 2020).

Lorenz et al. (2018) used Artificial Neural Networks (ANN) to estimate an up-to-date climate-based metric, Daylight Autonomy (DA). The study was carried out in three stages and the level of complexity was increased at each stage. First, a neural network is implemented and validated for a single design domain. In the second stage, the ability of artificial neural networks to predict DA levels according to changes in window design was tested. In the last stage, an ANN is applied to take into account the effects of the shading element. It is stated that the ANN model can predict simulated DA results for scenarios with and without shading. In another study, an ANN-based approach was developed to predict the lighting conditions in a work environment, taking into account the special needs of users. When constructing the model, both in situ illuminance and space utilization data for one year and simulation results were used to integrate all possible conditions. The proposed model was successful in estimating the illuminance level and lighting energy consumption in a working area based on user preferences (Katsanou, Alexiadis, and Labridis 2019). These studies have shown that artificial neural networks (ANN) can be used for many different purposes in the field of building physics.

Similarly, fuzzy logic models have various applications in the field of lighting, and studies using this method have been increasing in recent years. Logar et al. (2014) proposed a fuzzy black box model to predict indoor daylight illuminance. Solar radiation, external illuminance, position of blinds and illuminance measured from different points were used as inputs to the model. The small error rate (25 lux MAE, 12.60% RMSE and 7.76% MBE) of the model generated with 12-day measurements showed that this modelling approach can be integrated into larger test environments and used for indoor living comfort, energy saving, and artificial lighting control design. Kumar et al. (2020) developed a data analytics model-based control strategy for a daylight-artificial light integration scheme with data collected in an automated test room with adjustable LED fixtures and motorized blinds. The irradiance, temperature, altitude, and daylight illuminance measurements on the window are the variables used to predict the blinds' position on the windows on all four sides of the test room. Adjustable luminaire control signals are generated based on predicted optimum blind position and exterior lighting data. This method allowed the implementation of an industrial-level product and is used in an operating system with embedded WiFi. A similar study has developed a prototype of an IoT system that controls the balance of natural and artificial light with a dynamic shading system. With the control application designed with fuzzy logic model, seasonal automatic modes or manual functions can be adjusted by the user. While the required lighting threshold can be changed, the shading system acts according to seasonal profiles in line with bioclimatic design principles (Chiesa et al. 2020). In a study by Kunduracı and Kazanasmaz (2020), indoor illuminance was measured in three offices and eight different layouts, and manual lighting on/off behaviours of users were monitored. The obtained data were used to build a fuzzy logic model in the MATLAB FIS editor and the behavioural patterns related to the tendency to turn on the lights were classified. It is also stated that energy saving estimations/simulations can be made with such luminaire usage trend estimations and classifications. In another study, the fuzzy logic method was used to estimate the daylight illuminance to be obtained indoors according to different facade designs made in CAD programs. Calculations of solar radiation required for sufficient daylight and the size and position of windows are presented with classical and fuzzy models. It has been concluded that this technique can be applied effectively for indoor daylight evaluation while designing the building facade (Valiyev, Imamguluyev, and Ilkin 2020).

Overall, artificial intelligence (AI) models can be beneficial for optimizing lighting systems to minimize energy consumption while maintaining desired lighting levels. This optimization helps reduce costs, save energy, and decrease the carbon footprint. Such systems can be used to create personalized lighting solutions that enhance comfort and efficiency based on individual needs and preferences. By processing large volumes of data rapidly and accurately, these models facilitate a more efficient analysis of lighting performance and potential improvements. Fuzzy logic models and artificial neural networks (ANNs) can predict various lighting parameters—such as illuminance, colour temperature, light spectrum, light distribution, and energy consumption—to optimize lighting systems for energy efficiency, comfort, and productivity.

CHAPTER 3

METHODOLOGY

3.1. Experimental Design and Settings

In the study, two offices with similar features facing different facades were selected to investigate the effects of window glass types and LED luminaires with adjustable brightness/color temperature on indoor daylight quality, human health, office users' attention and work performance. The offices are located in the Faculty of Architecture, Block E, on the IZTECH Campus. The north-facing room measures 3.4m x 5.7m, whereas the south-facing one has dimensions of 6.65m x 4.5m (Figure 3.1). The Window-to-Wall Ratio (WWR) for the rooms is 33% and 35%, respectively. The ceiling height of the rooms facing north and south is 3.10 meters. The reason for selecting two orientations is that the north facade receives only diffuse daylight, while the south facade can capture both diffuse and direct sunlight. The characteristic nature of the light differs between these orientations, leading to a variation in the light spectrum. Figure 3.2 presents interior view, exterior view and window dimensions of the rooms.

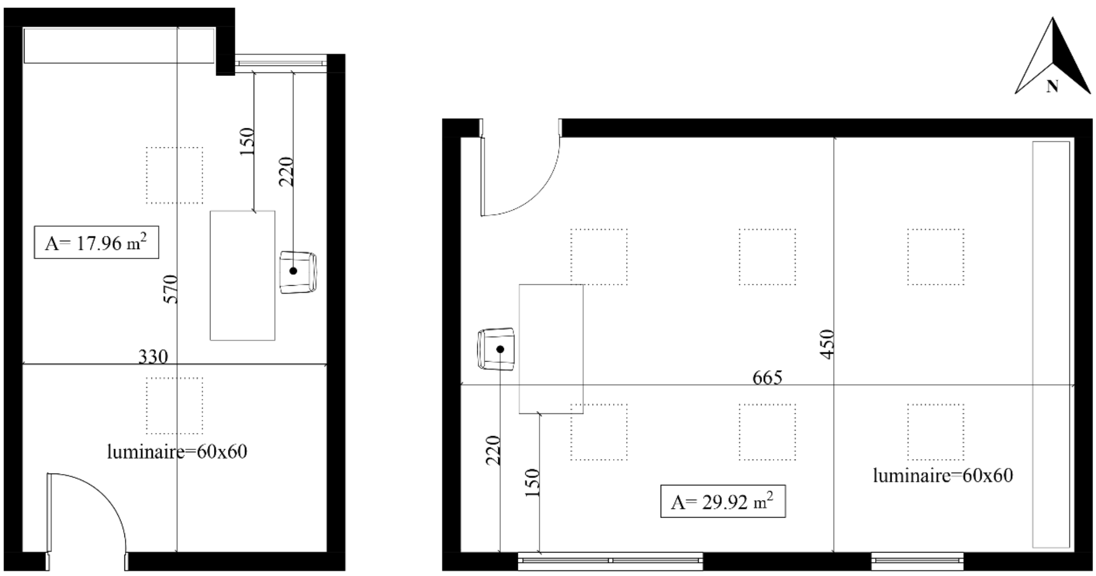


Figure 3.1. Plan view of the north-facing (left) and south-facing (right) rooms

Figure 3.2. Interior view, exterior view and window dimensions of north-facing (left) and south-facing (right) rooms

The walls of the offices are painted in cream colour, the ceiling is fitted with 60x60 cm suspended ceiling tiles, and the floor is covered with grey ceramic tiles. Each test room is furnished with a workspace desk, a chair, a bookshelf, and typical office items. The desks in the both rooms are positioned 150 cm away from the windows. The reflective properties of opaque materials such as walls, ceilings and floors, which affect the indoor illuminance level, were calculated using formula (3.1) by taking on-site measurements using illuminance meter and luminance meter and applying the method in the literature (Tregenza and Loe 2013; Jakubiec 2016):

$$L = (E \times \rho)/\pi \qquad \text{[Eq.3.1]}$$

Where L is luminance (cd/m2), E is illuminance (lux), ρ is reflectance of the surface.

The transmittance of existing clear glazing was determined in a similar way. The luminance of an object behind the glazing was measured in a direction perpendicular to the glazing surface once with the window closed and once with the window open. The transmittance clear glazing was found using following equation (3.2):

$$\tau = L_{in}/L_{out} \qquad \text{[Eq.3.2]}$$

Where L_{in} is the luminance of a specific point measured with glazing, L_{out} is the luminance of the same point measured without glazing. Based on this calculation, the existing windows in the room are composed of clear double glazing with a transmittance value of 90%. The optical properties of the materials are given in Table 3.1.

Table 3.1. The reflectance of the surface materials in the rooms

Surface	**Reflectance (ρ) (%)**
wall	86.62
floor	34.51
ceiling	92.19
door	10.24
desk	45.98
chair	18.75
cabinet	45.25

Nine types of window glass, which are often preferred in high-rise office buildings to provide solar and heat control and energy efficiency in the interior, have been determined to be tested in sample office rooms. The selected glass types include film coated solar low-e glasses, tinted/reflective glasses, electrochromic glasses and photovoltaic glasses in different color options (Table 3.2). In the decision-making process, various optical properties of the glass were considered, including transmittance, color rendering index (CRI), manufacturing method, material composition, and shading coefficient etc.

Table 3.2. Technical properties of window glasses

No	Glazing type	Layers (mm)	Transmittance (%)
G1	Clear, double	4 + 9 air + 4	90
G2	Smart glass	4 +12 air + 8	82/2 transparent/ opaque
G3	Solar low-e (neutral)	4 + 9 air + 6	50
G4	Low-e	4 + 9 air + 6	72
G5	Tinted solar low-e	6 smoked + 9 air + 4	39
G6	Tinted solar low-e	6 blue + 9 air + 4	49
G7	Tinted solar low-e	6 bronze + 9 air + 4	44
G8	Amorphous Silicon (A-SI) PV (Blue 0363)	4+4 blue PV+ 6 air + 4	40
G9	Amorphous Silicon (A-SI) PV (Orange 008E)	4+4 orange PV+ 6 air + 4	40
G10	Reflective	4 + 9 air + 6	21

Dynamic LED lighting systems were installed in both offices which are capable of dimming the indoor illuminance and changing CCT from 2700 K to 6500 K. One luminaire has a luminous flux of 3271 lm and its power is 30.7 W. The quantity and arrangement of the luminaires were determined to ensure an average illuminance of 500 lux throughout the room (Figure 3.3). Accordingly, four luminaires were installed in the north-facing room and six luminaires in the south-facing room. Light intensity and colour temperature could be adjusted simultaneously using a remote control app on the mobile phone (4remoteBT).

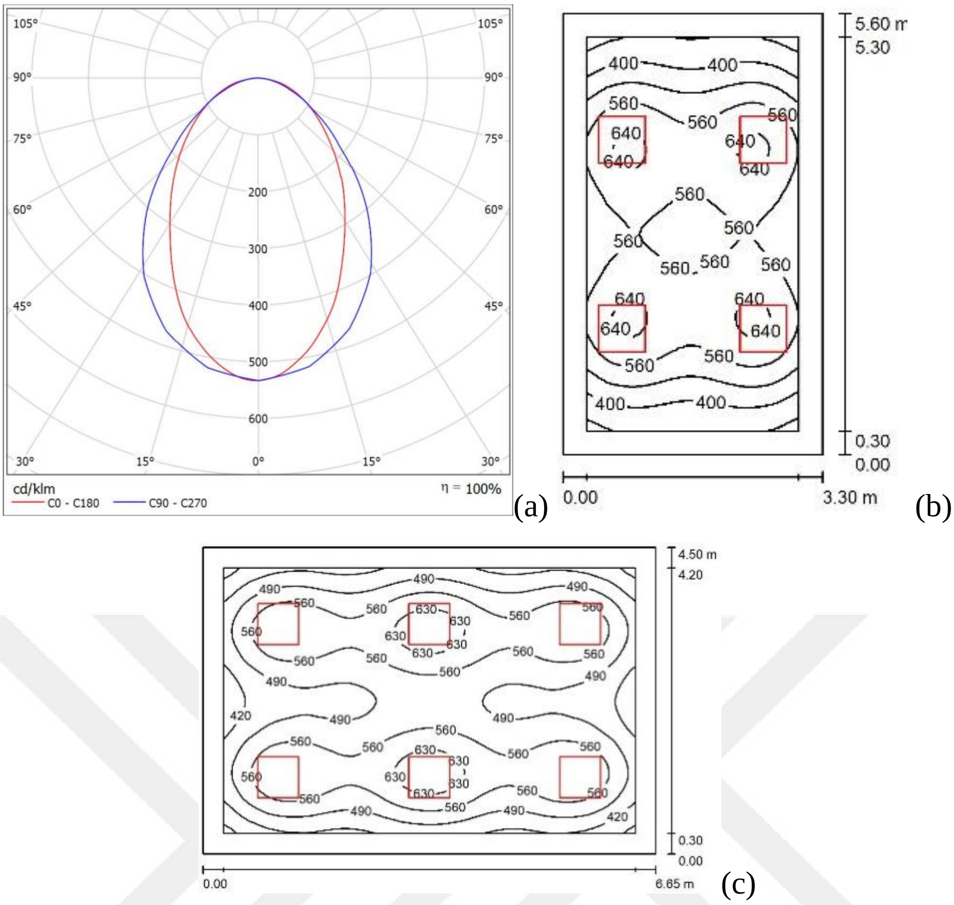


Figure 3.3. Candlepower distribution curves (a) and illuminance distribution in the north (b) and south (c) offices

The first main stage of the study is based on both objective measurement of lighting conditions on site and subjective task performances related to human health (sleepiness and mood), attention, perception, memory and satisfaction/preference of the lighting environment. This experimental part was carried out with a sufficient number of subjects to be suitable for analysis by statistical methods under various lighting conditions.

In the second main stage, the obtained data (measured objective data) is used to establish and test the artificial intelligence (artificial neural networks) model, and the subjective evaluations of the subjects are estimated. Also, fuzzy logic model is established and performance/satisfaction of participants are classified by considering objective measurements and subjective data together. The flow chart of the research method applied in the study is given in Figure 3.4.

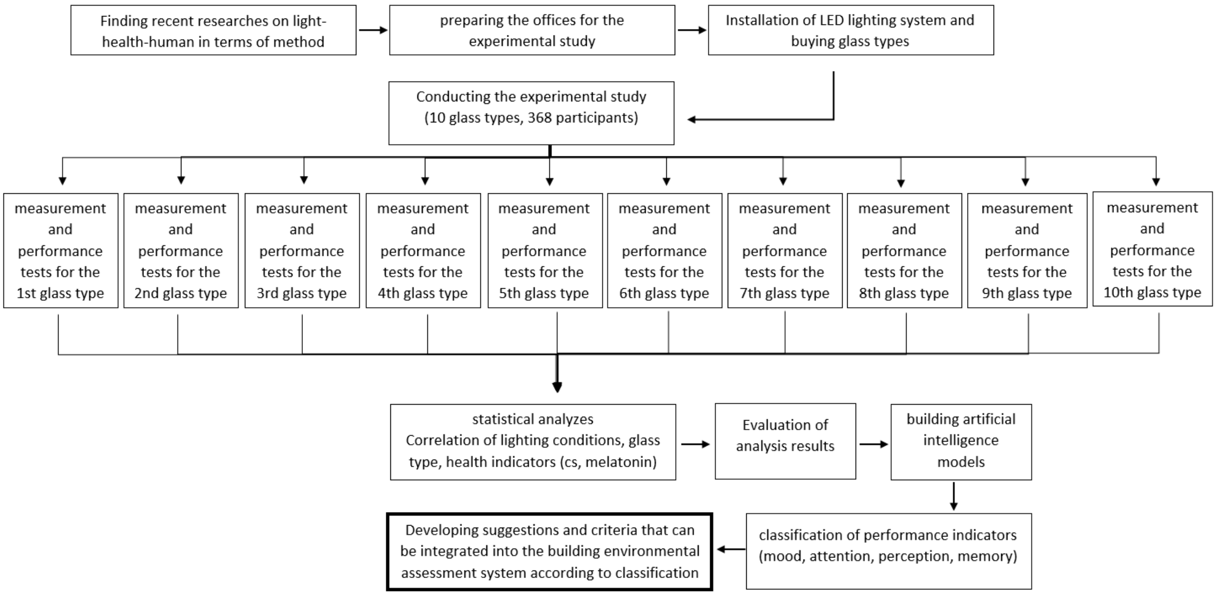


Figure 3.4. Flow chart of the research method to be applied in the study

3.2. Objective Measurements

The lighting assessments encompassed a comprehensive set of measurements. The measuring instruments utilized included the Konica Minolta CL-500A illuminance spectrophotometer, which was employed for illuminance, correlated colour temperature (CCT), and spectral power distribution (SPD) measurements, and the Konica Minolta LS-100 luminance meter, which was used for luminance measurements (Figure 3.5). The data collection forms, on which the measurements were recorded, are presented in Appendix A. Figure 3.6 illustrates the measurement points in two offices.

Figure 3.5. Spectrophotometer (left) and luminance meter (b) used during experiments

The lighting measurements conducted for each window glass alternative are as follows:

- Horizontal illuminance (lux), correlated colour temperature (K) and spectral power distributions (nm) from outside and inside the window
- Horizontal illuminance (lux), correlated colour temperature (K) and spectral power distributions (nm) on the workplane
- Luminance measurements (cd/m2) from specific points within the field of view
- Vertical illuminance (lux), correlated colour temperature (K) and spectral power distributions (nm) at eye-level of the person in a sitting position
- Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML)

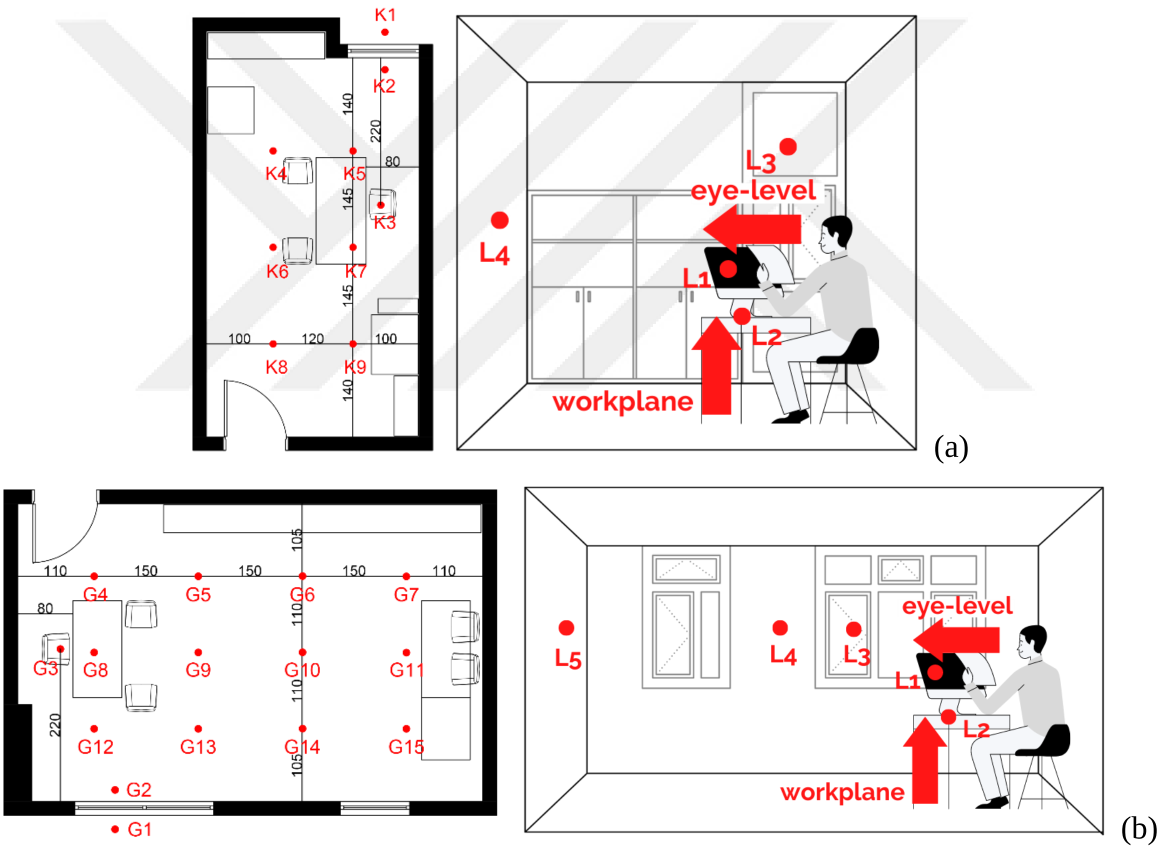


Figure 3.6. The location of the measuring points in the north (a) and south (b) facing room

The effect of a light source on the circadian system depends on several factors, particularly the amount of light entering the eye and its spectral power distribution (SPD). Among the various models proposed to date to determine the effect of corneal illuminance on the human circadian system, the most frequently used models are the Circadian Stimulus (CS) model and the Equivalent Melanopic Lux (EML) model. In the first model (Rea et al. 2010), circadian light (CLA) is calculated based on the distribution of spectral radiation in the cornea first, then the Circadian Stimulus (CS) value assuming a 1-hour light exposure and a constant pupil diameter of 2.3 mm (Eq.3.3) is obtained:

$$CS = 0{,}7 - \frac{0{,}7}{1+(\frac{CLA}{335{,}7})^{1{,}1026}} \qquad \text{[Eq.3.3]}$$

In this way, the CS value is designed to be equal to the percentage of melatonin suppressed. Thus, it can be used to assess the effect of light on human's circadian rhythm. The CS and EML values were determined using specialized calculation tools. The EML values were calculated with tools provided by the International WELL Building Institute, which simplify the measurement of melanopic illuminance for assessing lighting conditions' impact on circadian rhythms. Similarly, the CS values were derived using tools from the Lighting Research Center, which streamline the assessment of circadian stimulus based on light exposure. These tools facilitate accurate evaluation of how lighting affects human health and well-being.

3.3. Subjective Task Performances

In order to examine the non-visual effects of light on people, in addition to lighting measurements, some visual and cognitive performance tests were applied to office users and they were asked to evaluate the indoor lighting quality. The following tests were applied in order to determine the performance of the individuals:

Karolinska Sleepiness Scale (KSS): In this test, the subject rates their own sleepiness. It consists of evaluating a 9-point Likert scale with representative numbers from 1 to 9; for example, 1 means "extremely alert" and 9 means "almost sleeping". It is repeated for each change in lighting conditions to determine whether there is any decrease or increase in arousal level when subjects are exposed to different light levels or colour temperatures (Åkerstedt and Gillberg 1990).

Positive and Negative Affect Schedule (PANAS): This test aims to measure the participants emotional state and consists of two emotional dimensions. The test includes 20

Turkish adjectives that will create positive and negative effects. At the beginning and end of the experiment, subjects are asked to rate their current emotional state according to these adjectives on a 5-point Likert scale, with 1 = not at all and 5 = extremely (Gentile et al. 2018; (Watson, Clark, and Tellegen 1988).

Landolt Rings: This is a contrast/attention test. Subjects are given a piece of white paper containing 120 Landolt rings in light grey. A gap is left in one direction of the rings on the paper. Subjects are required to quickly identify and record the number of rings oriented in four possible directions (open on top, open on bottom, open left, open right) without marking the paper (Linhart and Scartezzini, 2011).

Stroop Test: This computer-based test requires constant attention and executive function. Subjects are required to respond as quickly and accurately as possible to the colour names (green, yellow, red, blue) displayed on the screen in different colour, and to press the corresponding button on the keyboard (e.g. 'G' for green, 'Y' for yellow, 'R' for red and 'B' for blue). The Stroop effect occurs when there is a mismatch between ink colour and word (e.g. the word GREEN is shown in red colour) (Leccese et al. 2019).

Short-Term Memory (N-back) Test: This test is applied to examine the executive functions and short-term memory of the participants. During the test, letters are presented in succession in the middle of the computer screen. Subjects are expected to evaluate whether the current letter matches the two digits before and to respond as quickly and accurately as possible by pressing mouse button (Zhu et al. 2017).

Written Questionnaire: A questionnaire was designed around terms such as (1) visual comfort and light level, (2) naturalness, (3) precision (of details and textures), and (4) satisfaction, and used to analyse participants' assessment of overall lighting quality. In the written questionnaire, there are a total of four question groups to be answered using a five-degree Likert scale with semantic opposites. Participants are expected to rate the environmental conditions within the framework of the determined topics from 1 to 5, with 1 = the most negative and 5 = the most positive (Arsenault, Hébert, and Dubois 2012; Çevik, Kazanasmaz, and Duran 2020).

Glare Sensation Vote (GSV): This method evaluates subjective discomfort caused by glare in indoor environments. At the end of each experimental session, participants' visual discomfort was assessed using the GSV scale. This scale utilizes a 4-point system, with responses ranging from 1 (imperceptible) to 4 (intolerable), to capture varying levels of glare-related discomfort.

Personal Information: The personal data of the participants were collected to assess whether participants' subjective evaluations are influenced by variables other than the lighting conditions. This information includes age, gender, profession, visual impairments (e.g., myopia, hyperopia) and vision aids (e.g., glasses, contact lenses), meal status, nighttime sleep duration, and satisfaction with indoor and outdoor air conditions.

The tests were organized in a specific sequence and presented to participants in written form, including detailed instructions. Considering the participant profile, the tests were prepared in Turkish. Participants completed the paper-based tests by marking their responses on forms, which were subsequently archived. Additionally, two computer-based tests, the Stroop test and the Short-term Memory test, were conducted using Psytoolkit to ensure standardized administration and reliable data collection (Stoet 2010; Stoet 2017). The written form include performance tests and questionnaire used during the experiments is given in Appendix B of this thesis.

3.4. Study Procedure

In order to determine the optimum lighting conditions in terms of human health, mood, attention and work performance by using various glass types together with adjustable LED lighting systems, healthy participants from various age groups with normal visual acuity were selected. The experiments began by adjusting the lighting conditions of the room to provide an illuminance of 300 lux on workplane in the north facing room. This was ensured by LED luminaires in case of insufficient light and the default CCT in the initial setting was 2700K. In the south facing room, only daylight was available in the initial setting. The existing shading elements were adjusted to be semi-opened in case of excessive sunlight. Once the lighting settings are completed, lighting measurements were taken at the points indicated in Figure 3.6. The participant was performed subjective performance tests in the lighting conditions determined in the first stage. There was a 10-minute break during which the participant was asked to adjust the color temperature (2700K to 6500K) and illuminance of the LED lighting as desired. Lighting measurements were taken for the new lighting conditions. Then subjective performance tests were repeated as in the first stage. The flow of the experimental stage and the estimated time are given in the Figure 3.7. The total time required for the experiment was approximately 90 minutes.

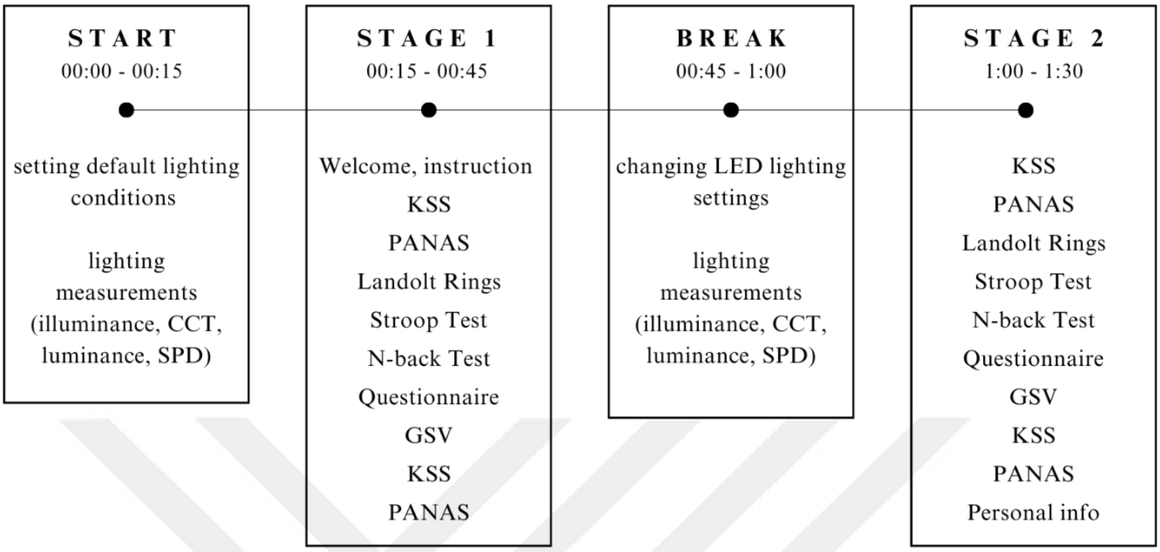


Figure 3.7. Detailed schedule of the experimental stage

For each glass type, the lighting measurements and the performance tests were repeated with default and preferred lighting settings. A minimum of 31 people for each glass type were included in the experiment to evaluate the lighting conditions generated in both rooms. Considering that a total of 10 different glass types are selected including the existing glasses, a total of 736 experiment executed with 123 males (mean age= 24.25) and 245 females (mean age= 24.33). Architecture faculty students and staff who do not have any mental or physical disorders to perform experimental tasks participated in the experiments. Performance tests and questionnaires were carried out each day at 9:00, 11:00, 13:00, and 15:00. Since it is a long-term study, the effect of glazing on the visual environment in different weather conditions was also examined. The date and time of the experiment for each participant were scheduled in advance. They are learned about the aim of the experiment, procedure, performance tests and questionnaire at the beginning of the experiment. Each participant signed a consent form stating that they participated voluntarily (see Appendix C for the participant consent documents). The application schedule of experiments according to glass types is shown in Table 3.3.

Table 3.3. The application schedule of glass types and experiments

Date	Glass Type	Room	Number of Participant
September-October	Clear Glass (G1)	North	18
		South	18
November	Smart Glass (G2)	North	18
		South	18
November-December	Solar Low-e (G3)	North	19
		South	20
December-January	Low-e (G4)	North	32
	Reflective (G10)	South	35
February	Solar Low-e Bronze (G7)	North	18
		South	19
February-March	Solar Low-e Blue (G6)	North	31
	Photovoltaic Blue (G8)	South	34
April-May-June	Solar Low-e Smoked (G5)	North	43
April-May-June	Photovoltaic Orange (G9)	South	45

3.5. Statistical Analysis

Statistical analyses in this study were meticulously carried out using a combination of t-tests, ANOVA, multivariate regression analyses, and Pearson correlation analyses (Gujarati and Porter 2009; Fisher 1925; Stigler 1989; Pearson 1895; Wright 1921). The initial phase involved conducting descriptive statistics and generating graphs to provide an overarching view of the collected measurements and experimental outcomes. Fundamental metrics such as mean and standard deviation were calculated, and graphical representations were created to summarize the key lighting measurements, circadian metrics, and performance test results. The schematic representation of data collection process is given in Figure 3.8.

To delve deeper into the relationships between the variables, correlation analyses were performed, focusing on the associations between performance indicators and various lighting parameters for each glass type. Specifically, metrics such as illuminance, luminance, correlated color temperature (CCT), and spectral power distribution (SPD) were correlated with task performance indicators to uncover any statistically significant relationships.

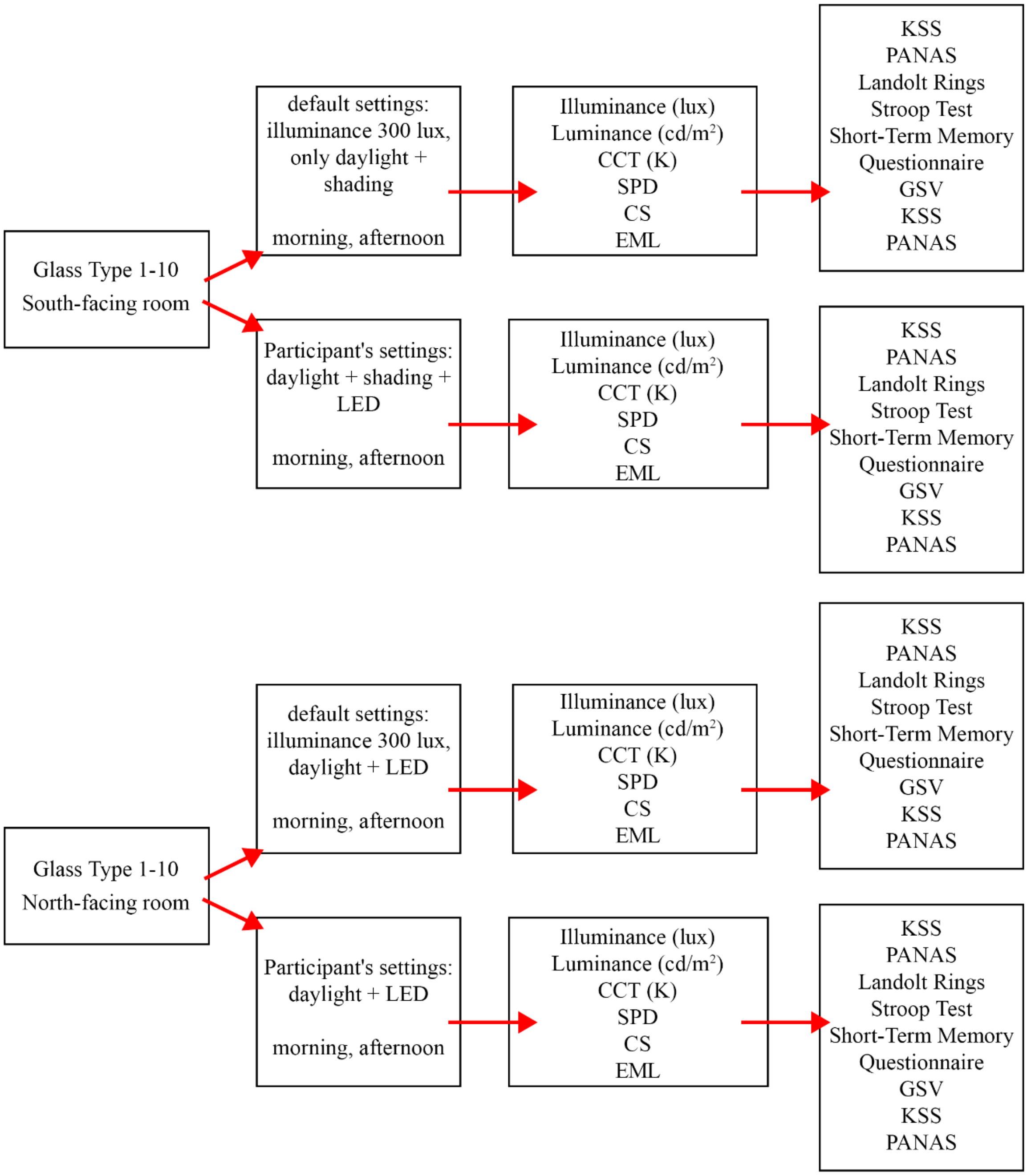


Figure 3.8. Schematic representation of data collection process

The statistical analysis results, including the comparison of task performance, subjective evaluations, and circadian measurements across the different groups, are summarized in Figure

3.9. T-tests were utilized to compare task performance and subjective evaluations between groups with low and high Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) values. ANOVA tests were applied to examine differences across groups categorized by average horizontal illuminance and LED color temperatures in terms of circadian measurements (CS, EML), task performance (e.g., Landolt, Stroop, 2-back), and subjective assessments (e.g., KSS, PANAS, GSV, survey).

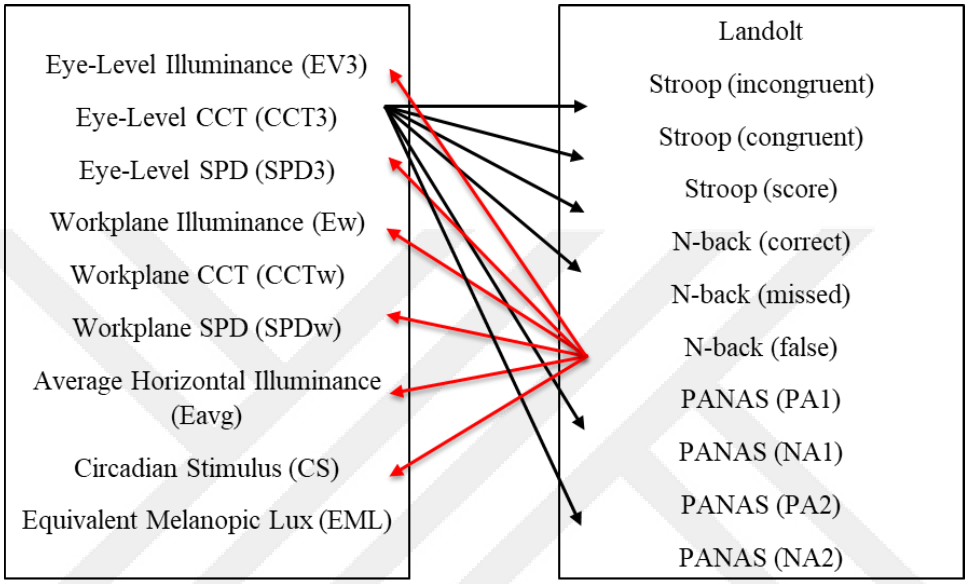


Figure 3.9. Statistical analysis chart (correlations)

Furthermore, a comprehensive multiple regression analysis was designed to assess the influence of lighting conditions, physical environmental factors, and personal data on performance indicators and subjective evaluations of office users. This analysis provided insights into the relative importance of different lighting variables, identifying the most significant factors affecting both performance and subjective evaluations (Figure 3.10).

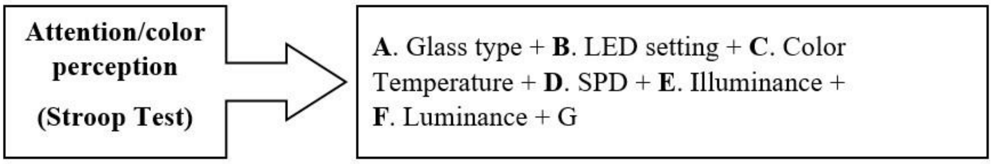


Figure 3.10. An example of a multiple regression model

The empirical organization, results, and explanations of these analyses are detailed in the subsequent sections of the thesis. The statistical software used for these analyses included SPSS, Lumivero-StatTools, R, and Excel.

3.6. Artificial Intelligence Models

The objective of this section is to predict performance indicators using Artificial Neural Network (ANN) models based on parameters such as illuminance, Circadian Stimulus (CS) values, Equivalent Melanopic Lux (EML), LED color temperature, Spectral Power Distribution (SPD), and glass types. The input parameters for the ANN models were selected based on the most relevant variables from the experiments and independent variables identified in the statistical analyses. Separate ANN models were developed for the results of Landolt, Stroop, and N-back tests, as well as for the survey evaluations concerning comfort, naturalness, precision, and satisfaction. Additionally, distinct models were created for Glare Sensation Vote (GSV), Karolinska Sleepiness Scale (KSS), and Positive and Negative Affect Schedule (PANAS). Figure 3.11 provides a schematic representation of the artificial neural network (ANN) model.

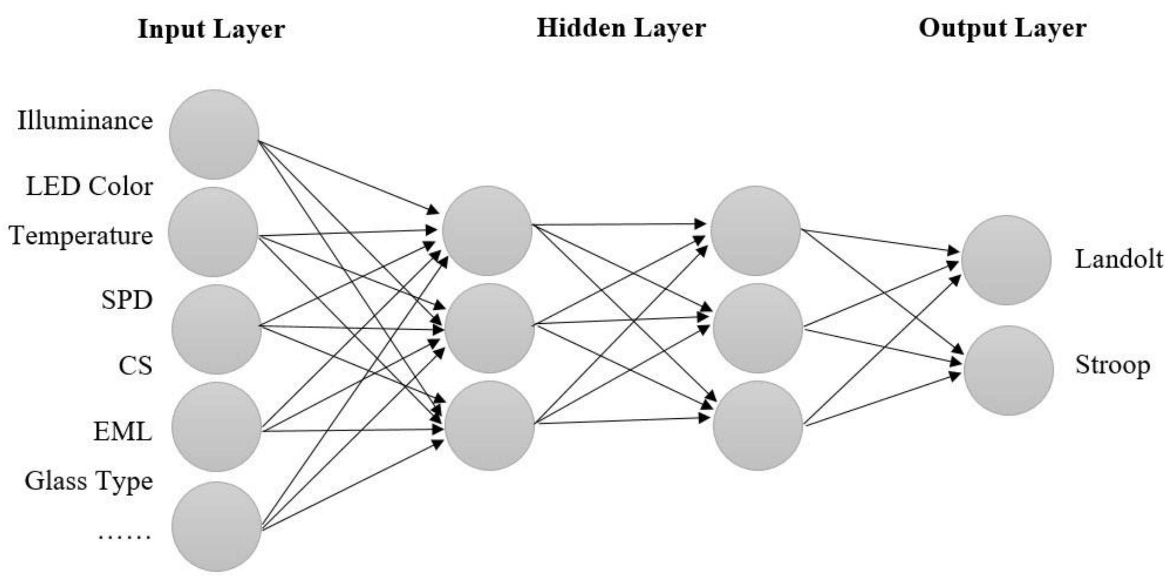


Figure 3.11. Schematic representation of artificial neural network (ANN) model

A similar approach was employed using fuzzy logic models, where the most influential parameters identified through both statistical analyses and ANN models were used to establish performance classes (low, medium, high) based on CS, illuminance, CCT, SPD, and glass type. Performance indicators were individually ranked from minimum to maximum values, with threshold values evenly distributed according to the data distribution. These indicators were then classified into low, medium, and high-performance groups (Figure 3.12). For instance, by categorizing the Stroop Score into low, medium, and high performance classes, it can be observed that specific combinations of environmental factors yield different outcomes. When the glass type is neutral blue, the Circadian Stimulus (CS) value is set at 0.3, the room is oriented south, and the LED color temperature is 4500K, participants tend to show moderate satisfaction with the lighting conditions and their attention levels are categorized as high. This indicates that under these particular conditions, the lighting environment positively impacts both user satisfaction and cognitive performance. Figure 3.12 illustrates a sample fuzzy logic classification used in the study. Such evaluations demonstrate that it is possible to create human-centric lighting conditions that not only maintain health but also enhance satisfaction and cognitive efficiency in office settings. By analyzing how these factors interact, recommendations can be made for optimizing lighting environments to achieve the best balance between health benefits and performance improvements.

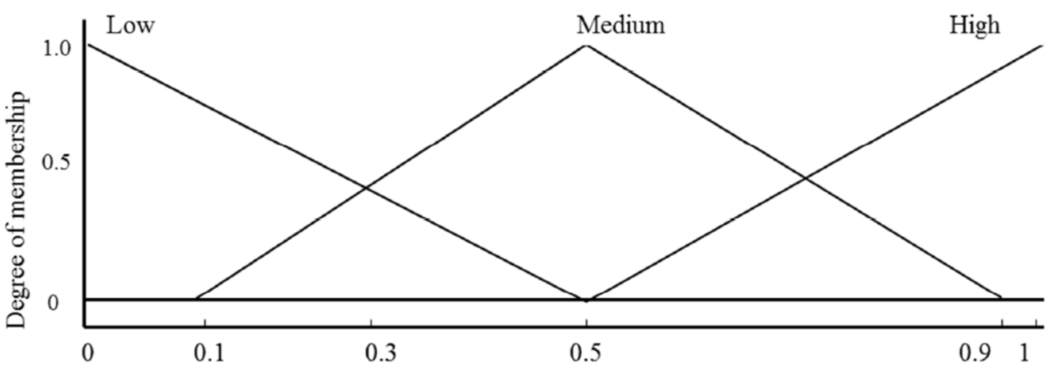


Figure 3.12. Schematic representation of Fuzzy Logic classification

CHAPTER 4

RESULTS

4.1. General Findings

4.1.1. Photometric Measurements

Measurements were conducted with the existing clear glazing windows to determine the lighting conditions of the rooms. The outdoor illuminance and correlated color temperature (CCT) values measured in the north and south-facing rooms on September 28, 2021, are presented in Table 4.1. The outdoor illuminance on the south-facing facade is consistently higher and shows greater fluctuation throughout the day compared to the north-facing facade. Before noon, the CCTs are higher, indicating a predominance of cooler light. Although a decrease in CCT values is observed in the afternoon, the light remained within the cool daylight range (5500K-6300K). Notably, the CCTs in the north-facing facade are generally higher than those in the south, suggesting that cooler light persists longer in the north-facing rooms.

Table 4.1. Elevation, azimuth, outdoor illuminance and CCTs on 28th September 2021

coordinates	38.325708, 26.630633		south facade		north facade	
hour	Elevation	Azimuth	Outdoor Illuminance (lx)	Sky CCT (K)	Outdoor Illuminance (lx)	Sky CCT (K)
09:00	20.89	110.63	5529.04	**8153.63**	2168.97	10458.55
11:00	40.42	137.42	64849.14	**5439.91**	1644.91	**11870.96**
13:00	49.47	178.43	93484.40	5532.01	2667.83	7789.92
15:00	41.43	220.22	65131.20	5473.64	2415.36	**6266.86**

The sky SPDs vary according to room location, atmospheric conditions, time of day and year. The spectral power is higher at all wavelengths in the south-facing room. In the north-facing room, the spectral power is higher at short wavelengths, while a rapid decrease is observed towards longer wavelengths. The highest spectral power distribution was obtained at 13:00 and 15:00 in the afternoon (Figure 4.1).

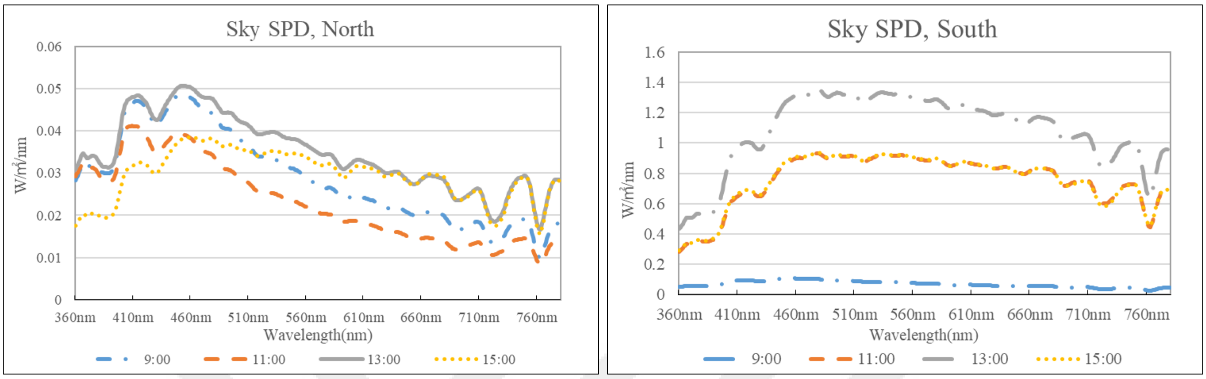


Figure 4.1. Sky SPDs for south and north facade on a clear sky day

Horizontal illuminance, CCT, and SPD values were measured indoors at specific points (K4-K9 and G4-G15 in Figure 3.6) using a spectrophotometer. Additional measurements were taken at eye-level (K3 and G3 points) in a vertical orientation. In the north-facing room, when the lights were off (LED dimmer set to 0%) and the room was solely illuminated by daylight, the spectral distribution was relatively even across all points, with a slight dominance in the 420-500 nm range. Notably, at point 4, which is near the window, there was an increase in spectral irradiance within the 420-460 nm range compared to other points, with values ranging from 0.003 to 0.004 W/m²/nm. In the south-facing room, under similar conditions (lights off, LED dimmer at 0%), the spectral distribution was also consistent across all points, but with a more pronounced distribution at wavelengths greater than 500 nm. At point 15, near the window, the dominant spectral irradiance increased beyond 500 nm, with values ranging from 0.003 to 0.0025 W/m²/nm. As the illuminance increased, the energy level rose accordingly, but the distribution pattern remained similar to that observed at other points (Figure 4.2).

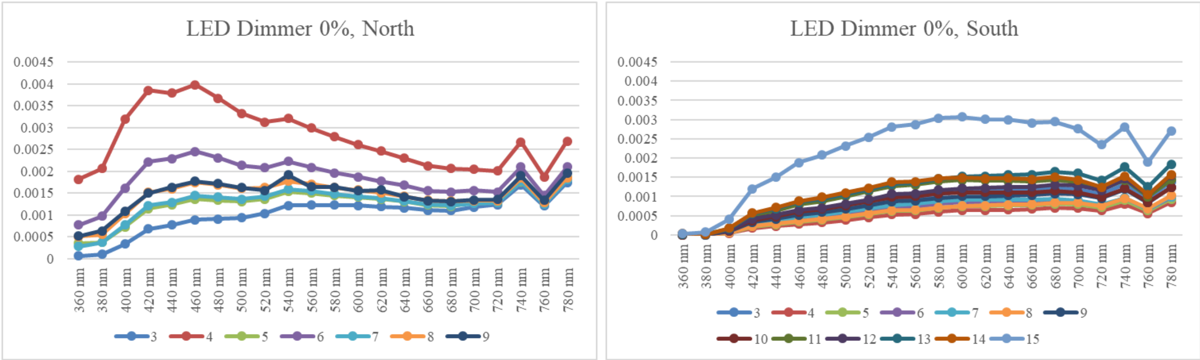


Figure 4.2. SPDs measured in the north and south-facing rooms with the LED lighting system off (September 27, 2021)

The variation in spectral power distribution with the use of artificial lighting was investigated through measurements conducted under different dimming and color temperature settings of the LED lighting system. The spectral distributions at 20%, 50%, and 100% dimming settings and at color temperatures of 2700K, 4600K, and 6500K for the LED lighting system in the north-facing room are illustrated in Figure 4.3. Distributions at the same color temperature exhibit similar characteristics, with energy levels varying proportionally with dimming settings. At 2700K, the spectral distribution shows the highest and most intense energy emission in the 600-620 nm range, while the energy at 450 nm is approximately half of that in the 600-620 nm range. At 4600K, the energy distribution is more homogeneous across the 500-660 nm range (with a slight increase in the 600-620 nm range), but the energy at 450 nm is about 1.5 times greater and more concentrated in this region. At 6500K, the distribution in the 500-660 nm range becomes even more uniform and flat, with increased values at 450 nm compared to the previous conditions, highlighting a dominance of blue light. The SPD distribution measured vertically at eye-level at point 3 shows a similar pattern to other points but with lower energy distribution.

Figure 4.4 shows the SPD measurements in the south-facing room with the LED lighting system at dimming levels of 20%, 50%, and 100%, and at color temperatures of 2700K, 4600K, and 6500K. Distributions at the same color temperature exhibit similar characteristics, with energy levels varying proportionally according to the dimming settings. The trends observed in the north-facing room are comparable to those in the south-facing room. However, energy levels in the south-facing room are generally higher than those measured under the same conditions in the north-facing room, likely due to differences in the room's physical conditions and the significant impact of daylight despite the presence of blinds in the south-facing room.

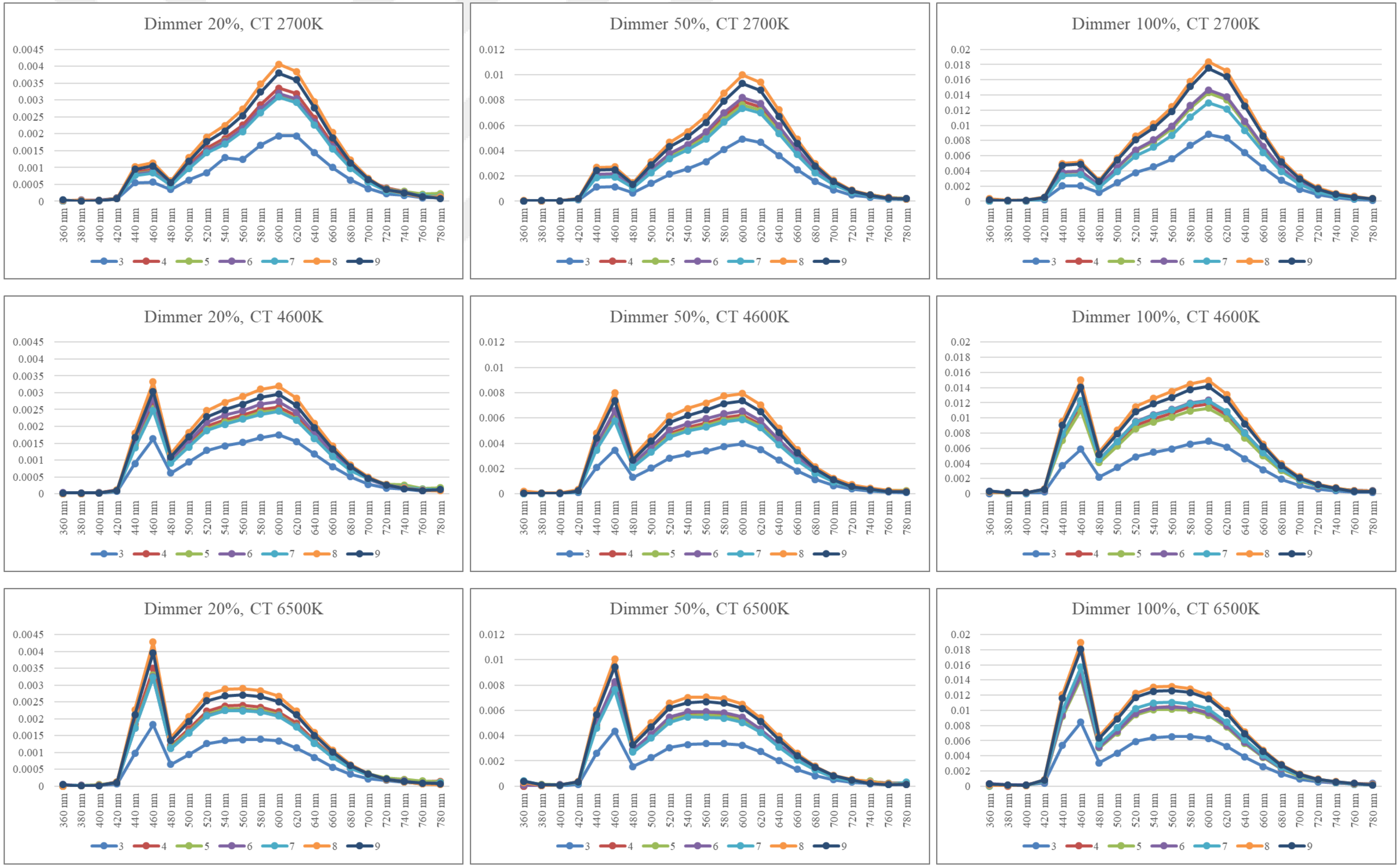


Figure 4.3. The SPDs in the north-facing room according to the settings of the LED lighting system

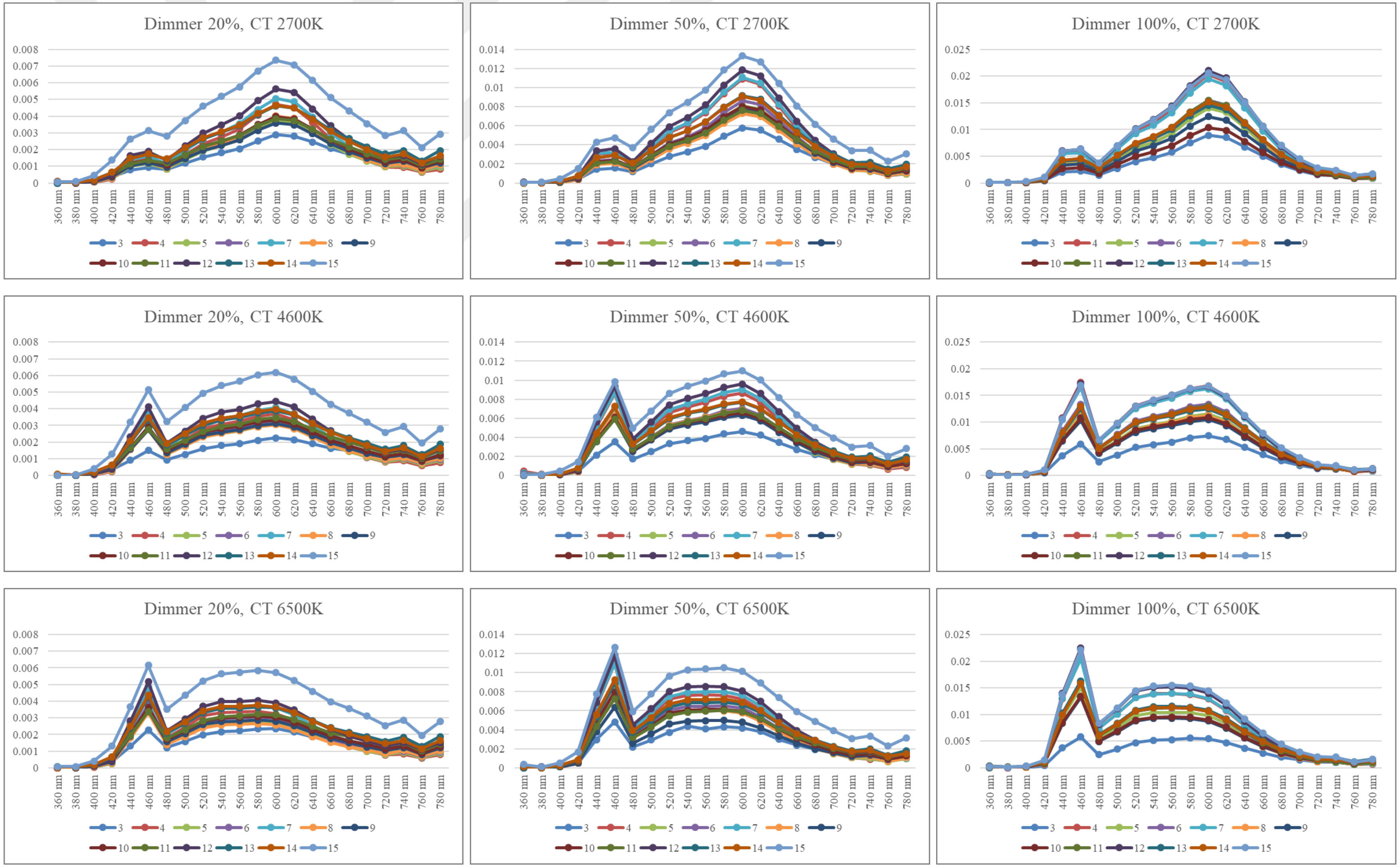


Figure 4.4. The SPDs in the south-facing room according to the settings of the LED lighting system

Figure 4.5 presents the distributions of all illuminance and CCT measurements at eye-level as well as workplane. Illuminance are primarily around 330 lux at eye-level and 400 lux at the workplane. CCTs predominantly fall within the range of 3000K-6000K, both at eye-level and at the workplane. The coefficient of determination (R^2) between illuminance values at the workplane and eye-level is 0.76, while for CCT values at the same locations, R^2 is 0.88. These coefficients indicate the degree of correspondence between measurements taken at the workplane and eye-level, with values closer to 1 reflecting a stronger correlation and greater agreement between the two measurement points.

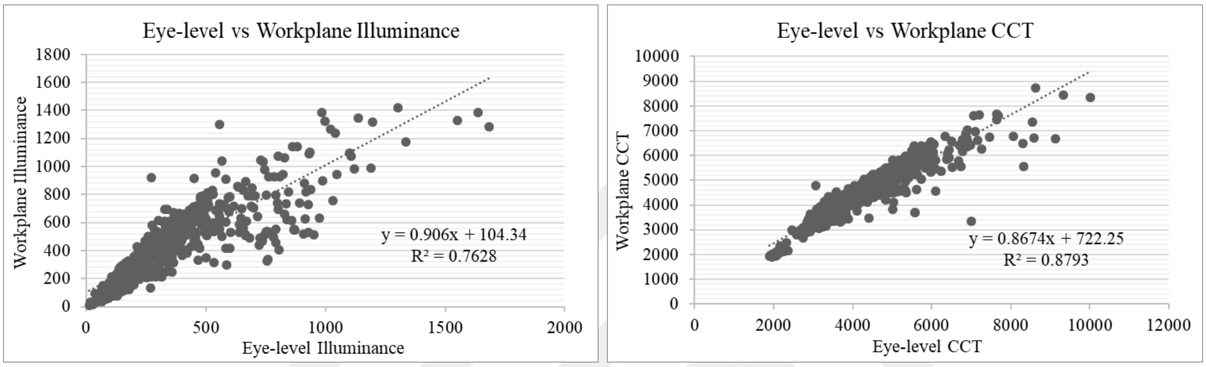
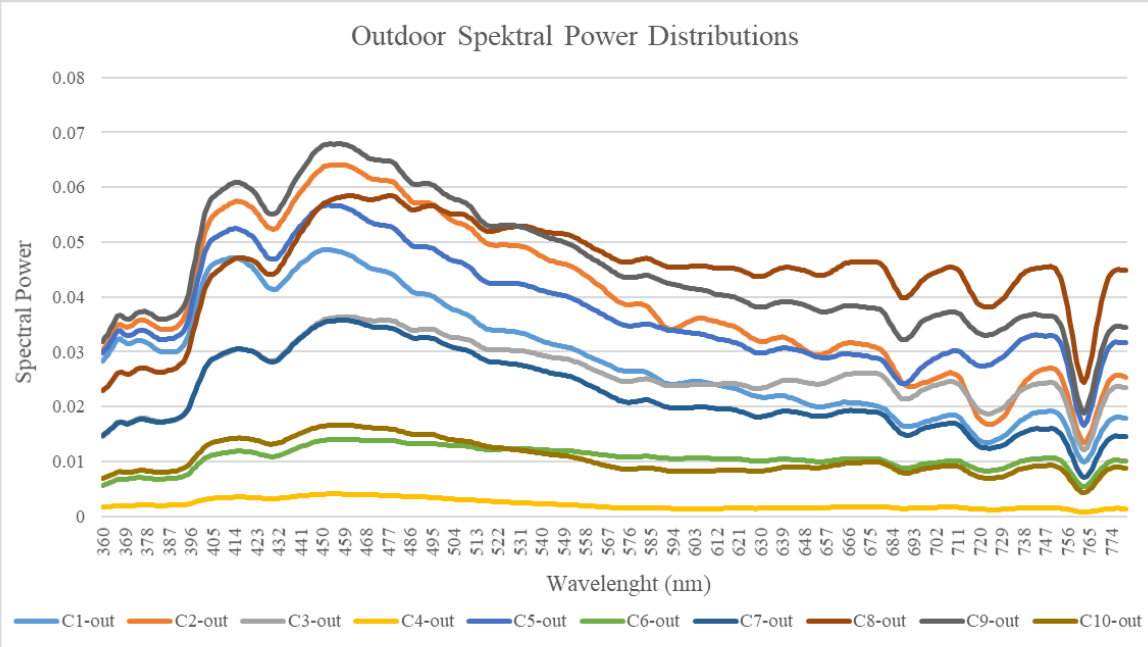


Figure 4.5. Comparison of eye-level vs workplane illuminance and CCT values

SPD measurements taken from inside and outside the window were examined with graphs to reveal how glass types change the daylight character (Figure 4.6). Spectral power distributions for different window glasses on clear and intermediate sky days are shown in Figure 15. The SPDs measured through window show that each glass type modifies the spectral distribution of daylight differently. However, for all types of glazing, the indoor spectral power density is lower compared to outdoor measurements. Clear glass (G1), smart glass (G2), low-e (G3) and solar low-e glasses (G4) showed a relatively neutral behaviour and became the glasses that disrupted the daylight spectrum the least. Tinted solar low-e glasses (G5, G6, G7) modified the colour characteristic of daylight presenting denser/higher energy released around 520-600 nm and 600-650 nm, resulting in peak values at 560 nm. The spectral distribution through the reflective glass (G10) shows similar trend where it takes its highest value at 555 nm. Another increase can be noted in the range of 450-520 nm, corresponding to the blue colour spectrum. The most remarkable alteration in the daylight spectrum occurs in photovoltaic glasses. Daylight through blue PV glass (G8) shows a completely different trend than sky SPD. The spectral distribution of daylight through blue PV glass shows a jump between 400-570 nm and peaks at 500nm which corresponds to blueish color. When orange PV glass (G9) is applied, the spectral power distribution follows the opposite trend, taking its lowest value at the shorter wavelengths and increasing at 570 nm, following the same trend with the sky SPDs up to 780 nm. This made the objects in the environment to appear reddish-orange. SPD plots generated separately for each glass type are given in Appendix D.



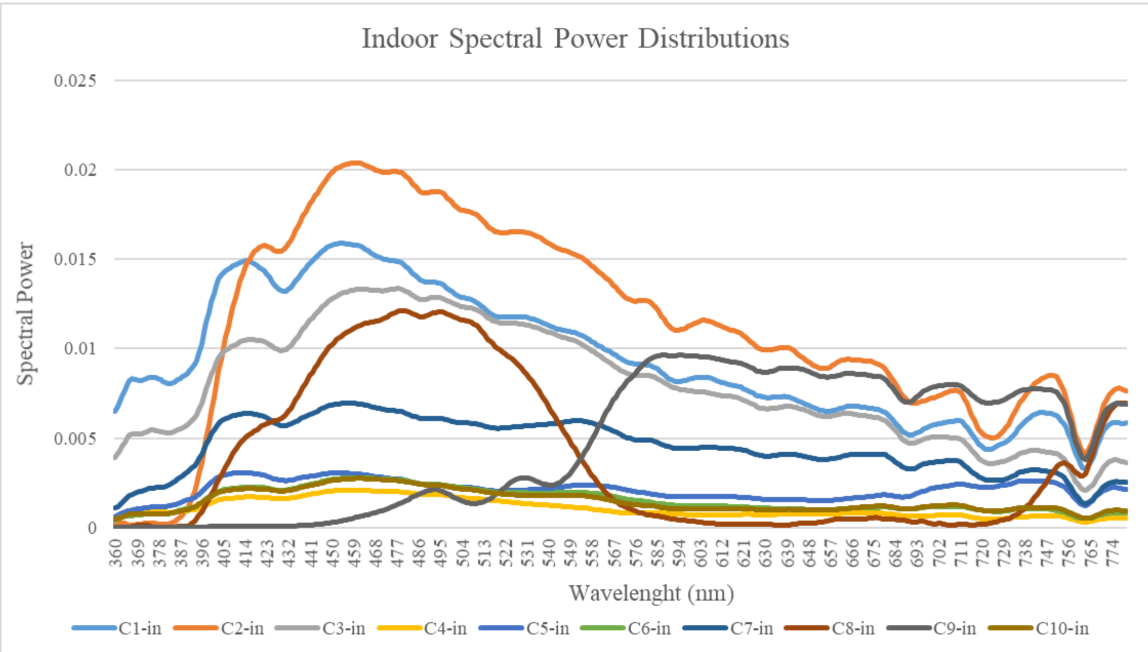


Figure 4.6. Indoor and outdoor SPDs taken at 9 am for glass types.

Table 4.2 presents illuminance measurements at both eye-level and the workplane, as well as the LED dimmer settings of participants for various glass types (G1-G10). The type of glass used significantly impacts both indoor illuminance and the required LED dimmer settings. There is a significant reduction in illuminance when moving from outdoor to indoor environments across all glass types. This reduction is expected due to the filtering effect of the glass, which decreases the amount of light that penetrates into the indoor space. Orange PV glass (G9) allows the highest outdoor illuminance (32641 lux), but the indoor illuminance drops significantly, especially at eye-level (138 lux). However, it still requires a higher LED dimmer setting (68%) compared to other glass types. Clear glass (G1) and smart glass (G2) also show relatively high outdoor illuminance but maintain better indoor illuminance levels compared to orange PV glass (G9). The LED dimmer settings for these glass types are moderately high, suggesting that even with higher natural light, artificial lighting is still needed to achieve desired indoor conditions. Indoor illuminance at the workplane tends to be higher than at eye-level, which is consistent with the expectation that light intensity is greater closer to the source or when measured on horizontal surfaces where task lighting is more effective. The LED dimmer settings vary from 54% to 68%, reflecting users' adjustments based on the amount of natural light provided by different glass types. Higher dimmer settings, like those seen with G9 and G10, suggest that even with a higher natural illuminance, users prefer brighter artificial lighting, possibly due to lower light quality or uneven distribution of natural light indoors. Conversely, lower dimmer settings, such as those for clear glass (G1) and blue solar low-e glass (G6) (both at 54%), suggest that these glass types provide sufficient natural light, reducing the need for intense artificial lighting. Glass types that allow more natural light penetration generally result in lower LED dimmer settings, though this relationship is also influenced by the specific indoor illuminance distribution and user preferences for brightness.

Table 4.3 presents the CCT measurements and LED color temperature settings based on the different glass types (G1-G10). Indoor CCT values are generally different than outdoors, reflecting the influence of glass filtering. The results show that different glass types significantly impact the CCT of indoor environments. Participants seem to adjust the LED color temperature settings to compensate for the color temperature of the natural light filtered through the glass, either to warm up or cool down the indoor lighting. For clear glass (G1), solar low-e glass (G4), and smoked solar low-e glass (G5), there is only a slight change in CCT values when transitioning from outdoor to indoor environments, suggesting that the glass types have a minimal effect on altering the daylight's color characteristics. In the cases of smart glass (G2) and bronze solar low-e glass (G7), the CCT values indoors show a moderate decrease, ranging around 6000K-7000K. This indicates a noticeable but not drastic shift in color temperature as the light passes through the glass. Low-e (G3) and reflective (G10) glasses, however, exhibit an increase in CCT values indoors, which suggests that these glass types might be influencing the light to appear cooler or more bluish when inside the space. Blue PV glass (G8) shows a dramatic shift, with notably high indoor CCT values indicating a substantial change in light quality. This suggests that the glass type allows a significant amount of cooler light to penetrate indoors, possibly even enhancing the cooler tones of daylight. In contrast, orange PV glass (G9) exhibits extremely low indoor CCT values (approximately 2000K), indicating that the indoor environment experiences very warm, almost orange light. This could be due to the glass type filtering out most of the blue light, creating a very warm interior. Users compensate by setting the LED color temperature to a higher 4698K to achieve a more balanced lighting environment. Across all glass types, the CCT at eye-level and the workplane are similar, reflecting a consistent indoor lighting environment. This consistency is important for tasks that require uniform lighting. Participants tend to select LED color temperatures that are warmer than the natural light provided by the glass, which suggests that the glass types in question generally cool down the natural light, and participants prefer to warm it back up using artificial lighting.

Table 4.2. Average illuminance and LED dimmer preferences by glass type (G1-G10)

Glass Type	**Outdoor**	**Indoor**	**Stage 1**		**Stage 2**		**LED Dimmer Setting (%)**
			Eye-level	**Workplane**	**Eye-level**	**Workplane**	
G1	23352	14072	498	468	554	632	54
G2	14768	6333	508	463	544	600	58
G3	6671	2039	313	417	528	576	60
G4	1652	661	144	195	279	421	56
G5	3145	520	157	230	311	465	62
G6	3426	644	165	232	277	414	54
G7	19098	6935	290	331	526	653	63
G8	18221	1676	96	87	329	434	62
G9	32641	3385	138	124	389	536	68
G10	27094	5474	381	284	517	706	67

Table 4.3. CCT values and LED color temperature preferences by glass type (G1-G10)

Glass Type	**Outdoor**	**Indoor**	**Stage 1**		**Stage 2**		**LED CT Setting**
			Eye-level	**Workplane**	**Eye-level**	**Workplane**	
G1	8445	8009	5266	5212	4523	4576	4050
G2	8513	6840	4933	4902	4384	4550	4261
G3	8518	9159	4861	5142	4590	4889	4565
G4	10978	10089	3390	3530	4085	4480	4039
G5	10485	10119	3402	3551	4329	4692	4442
G6	6875	11253	3589	3786	4424	4779	4297
G7	7958	6184	3962	4103	4254	4525	4521
G8	6166	81344	42356	39438	7859	6954	4794
G9	7847	2078	2084	2049	3240	3659	4698
G10	5856	6674	5986	5990	5000	5228	5011

The average of the indoor horizontal illuminance measured from the points shown in Figure 3.6 (G4-G15 and K4-K9) was divided into three groups as less than 300 lux (1), between 300-750 lux (2), and greater than 750 lux (3). According to this classification, 38% of the average illuminance is above 750 lux, 50% is between 300-700 lux, and 12% is below 300 lux. Further, the lighting conditions in the room were divided into four groups: daylight only (1), LED above 5000K (2), LED between 4000K-5000K (3) and LED below 4000K (4). As a result, 37% of the experiments were carried out when there was only daylight in the room, 16% when the LED was above 5000K, 25% of the experiments were carried out when the LED was in the range of 4000K - 5000K, and 22% when the LED was below 4000K (Figure 4.7).

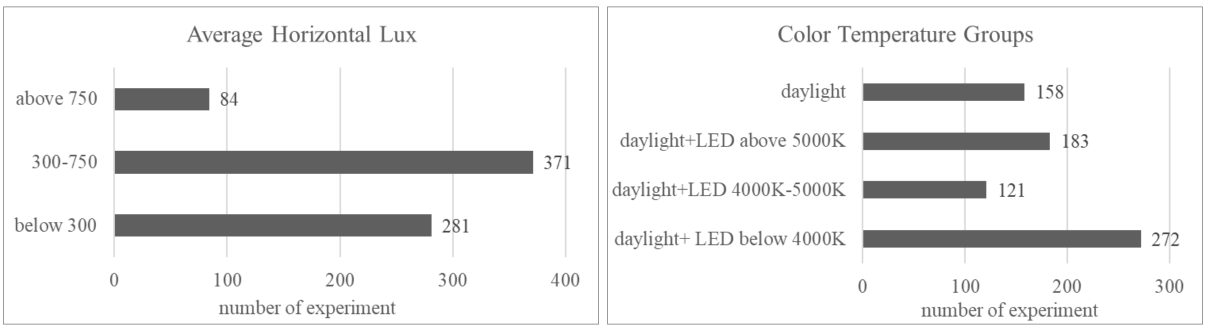


Figure 4.7. Number of experiments in the illuminance and LED colour temperature groups

To assess glare distributions and the presence of discomfort glare within the rooms, luminance (cd/m²) measurements were taken from various surfaces, including the glass surface, a wall surface near the window, the wall surface opposite the seated person, the computer screen, the desk surface, and the cabinet surface. These measurements were taken for each lighting condition at both the first and second stages. Figure 4.8 presents a schematic representation of the rooms, highlighting the designated luminance measurement points.

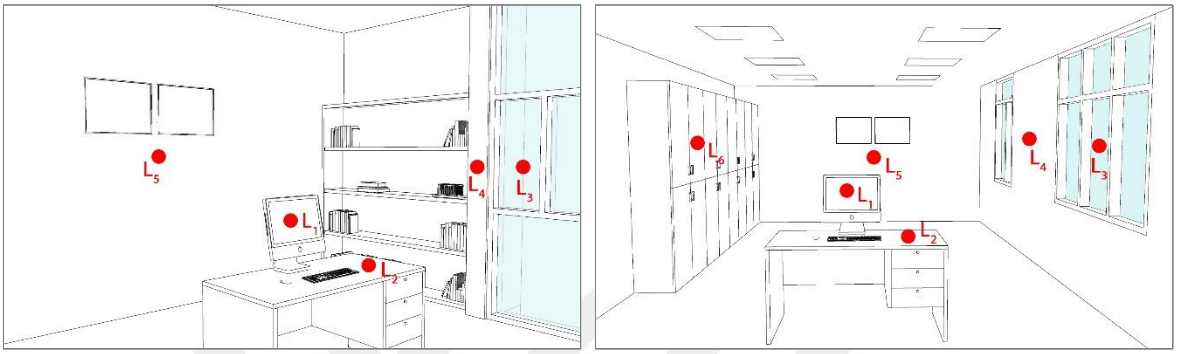
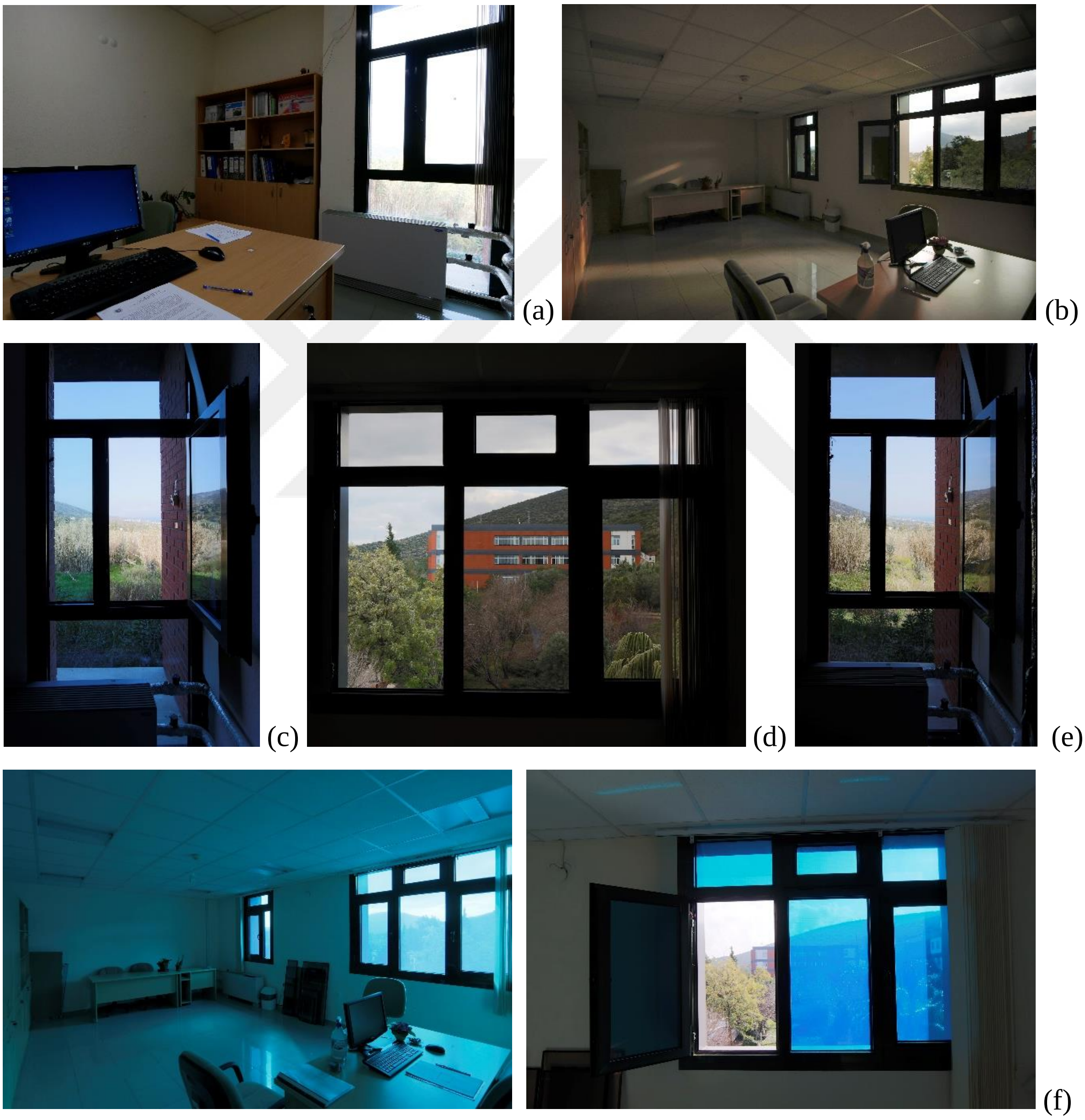


Figure 4.8. Schematic representation of the north (left) and south (right) facing rooms with luminance measurement points

When analyzing the luminance values for the wall opposite and the desk (L5/L2) with the existing clear glass installed, it was found that the glare ratio did not exceed 1:10 or 10:1 in both the north and south rooms. This ratio was consistently maintained across all glass types examined. For the glare ratios between the workplane and the computer screen (L2/L1), only 23 out of 72 measurements met the 1:3 or 3:1 ratio, with 10 of these measurements occurring in the south room. Among the initial stage measurements, only 10 values adhered to these criteria. No significant variations were observed based on room orientation, experimental stage, or time, though changes in workplane illuminance due to external weather conditions could have influenced these results. Regarding the glare ratio between the wall opposite and the computer screen (L5/L1), most measurements adhered to the 1:10 or 10:1 ratio, with only 4 measurements exceeding this range. In the presence of G2, glare ratios between the desktop and computer screen (L2/L1) exceeded the expected values in 40 out of 72 measurements, ranging between 4:1 and 9:1, regardless of the room orientation. A similar trend was observed with G3, where significantly higher values, such as 158:1, were recorded. In the case of G10, glare ratios exceeded the expected values in 27 out of 70 measurements, indicating a high likelihood of discomfort glare. Additionally, glare ratios exceeding the 3:1 ratio were noted in 19 measurements for G4, 38 for G7, 30 for G6, 5 for G8, 17 for G9, and 43 for G5. Despite these ratios, participants' responses to the Glare Sensation Vote (GSV) generally indicated a perception of discomfort glare as either slight or noticeable. It is suggested that the positioning of the desk and seating arrangement, which shifted the view of the windows out of the direct line of sight, rendered the L3/L2 ratio less effective. Consequently, the perception of glare was more significantly influenced by the L5/L2 and L5/L1 ratios. Figure 4.9 displays the interior views of rooms equipped with various types of glass.



(g)

Figure 4.9. Interior view of rooms with different glass types: (a) smart glass, (b) reflective glass, (c) blue solar low-e glass, (d) bronze solar low-e glass, (e) smoked solar low-e glass, (f) orange PV glass and (g) blue PV glass

4.1.2. CS and EML Values

EML and CS value, which are indicators of the effect of light on the human circadian system, were classified according to the threshold values specified in the standards. CS value of at least 0.3 or more is recommended by Lighting Research Centre to effectively stimulate the circadian system and is associated with better sleep and behaviour/mood. Similarly, the WELL Standard recommends providing an EML of 250 for at least four hours in the vertical plane at eye-level for workplaces. According to overall data collected, the CS value was below 0.3 in 55% of the experiments, while it was 0.3 and above in 45%. This rate is almost the same for EML. The number of experiments failing to meet the threshold value is higher in the north-facing room and in the first stage. Figure 4.10 shows the percentages of experiments that exceeds and fell below the threshold EML and CS values by room orientation and experimental stage. The mean CS and EML values for glass types are given in Appendix C.

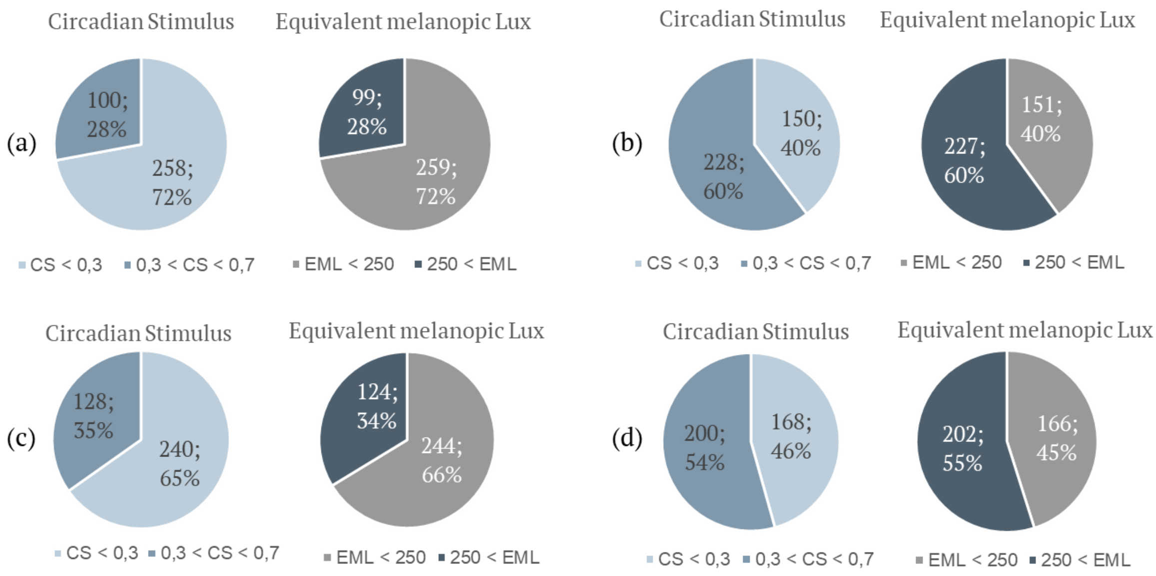
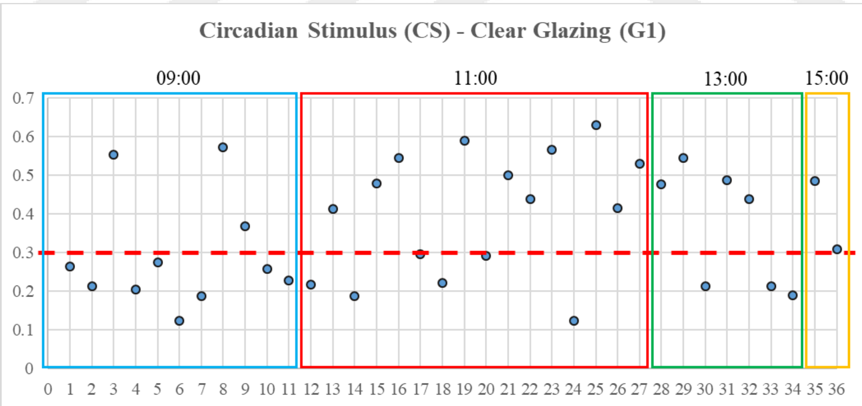
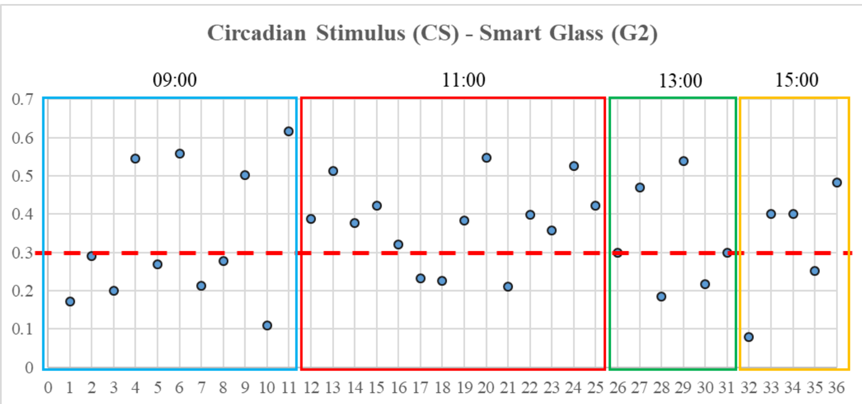


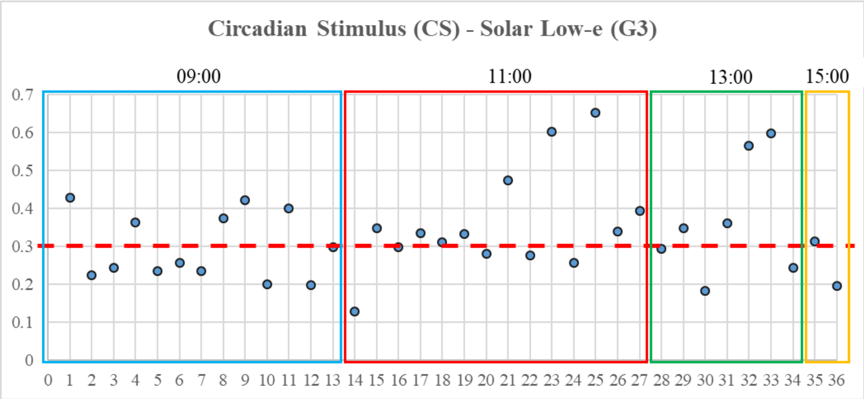
Figure 4.10. CS and EML percentages for (a) north, (b) south, (c) first and (d) second stage

The CS and EML values were systematically analyzed across different time intervals to understand the impact of LED preferences and glass types on circadian lighting conditions. The distribution of these values for each glass type and time of experiment is presented in Figure 4.11 and Figure 4.12. The visualized data presents the variations in CS and EML values recorded during the second stage of the experiment, in which dynamic LED lighting was utilized. Under the existing clear glass (G1) conditions, most CS values at 9 am were below 0.3, indicating minimal circadian impact during early morning hours. However, at 11 am and 1 pm, these values increased above 0.3, aligning with literature suggesting this time period is ideal for tasks requiring heightened attention. When both LED lighting and daylight were present, the EML values exceeded 250 lux at 9 am, 11 am, 1 am, and 3 pm, suggesting sufficient melanopic lux throughout the day. With smart glass (G2) installed, the majority of CS values at 9 am remained below 0.3, similar to the clear glass scenario. However, after 11 am, most values rose above 0.3. The EML values followed a similar trend, remaining below 250 lux in the early morning but surpassing this threshold for the rest of the day. For low-e glass (G3), the pattern was consistent with the smart glass, where most CS values at 9 am were below 0.3. Even those above 0.3 were lower than the values observed with the clear glass. Participants tended to prefer lighting conditions with lower illuminance. After 11 am, the CS values varied, with those for smart glass distributed between 0.3 and 0.6, while for low-e glass, the range was narrower, between 0.3 and 0.4. Despite its lower transmittance compared to smart glass, participants selected lower illuminance under low-e glass.

When neutral solar low-e glass (C4) was used, most CS values remained well below 0.3 throughout the day. Despite having higher transmittance than G3, participants chose even lower illuminance levels. With smoked solar low-e glass (C5), afternoon CS values were predominantly below 0.3, but EML values consistently exceeded 250 lux throughout the day. A similar pattern was observed with blue solar low-e glass (C6), where only at 11 am did the CS values exceed 0.3. The discrepancy might be due to the impact of blue and smoked glass on the LED color temperature choice, given the low transmittance values of 0.40 to 0.44. Under blue PV glass (C8), CS values remained above 0.3 throughout the day, influenced by the dominant blue color of the glass. EML values were below 250 lux in the early morning but exceeded this level for most of the day. Orange PV glass (C9), CS values were below 0.3 in the morning but increased significantly in the afternoon. EML values stayed above 250 lux throughout the day, with the morning discrepancy potentially caused by the dominant orange hue of the glass. Finally, with reflective glass (C10), CS values remained above 0.3 all day, though they dipped slightly at 3 pm. Participants appeared to select lighting conditions that were more comfortable in terms of light quality, while still maintaining suitable conditions for tasks requiring sustained attention throughout the day.



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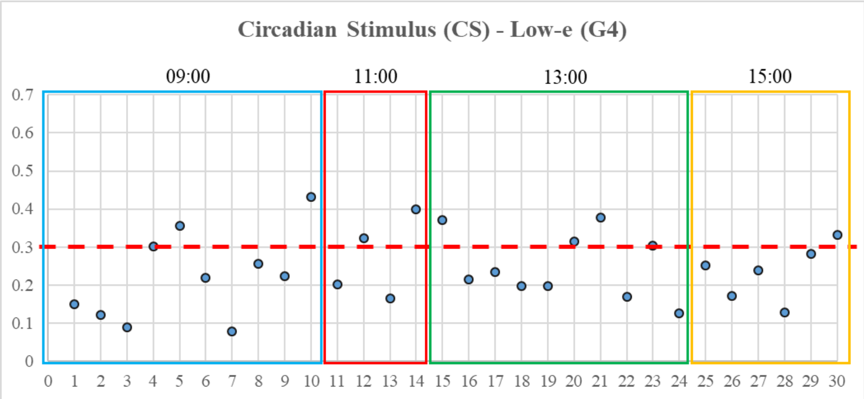
11:00
13:00
15:00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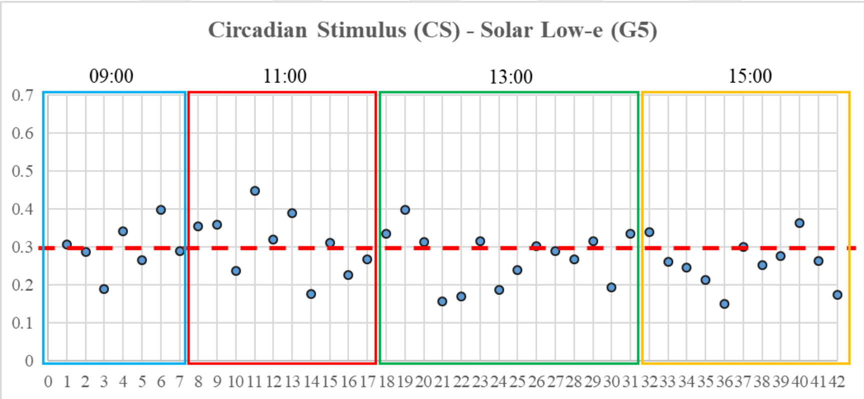
15:00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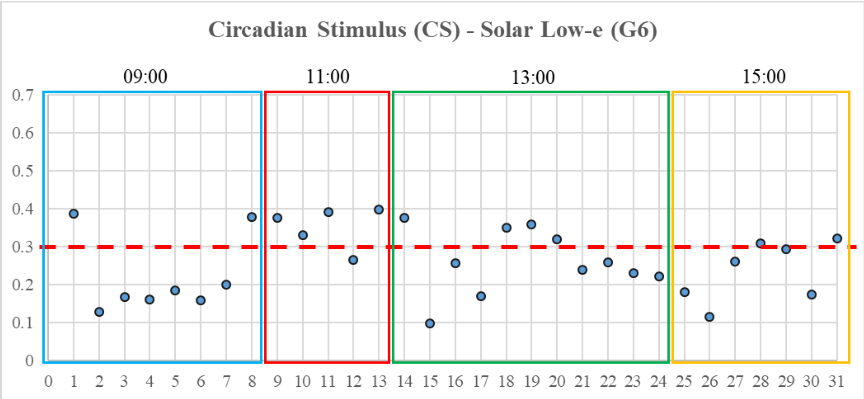
13:00
15:00


Circadian Stimulus (CS) - Solar Low-e (G6)
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11:00
13:00
15:00

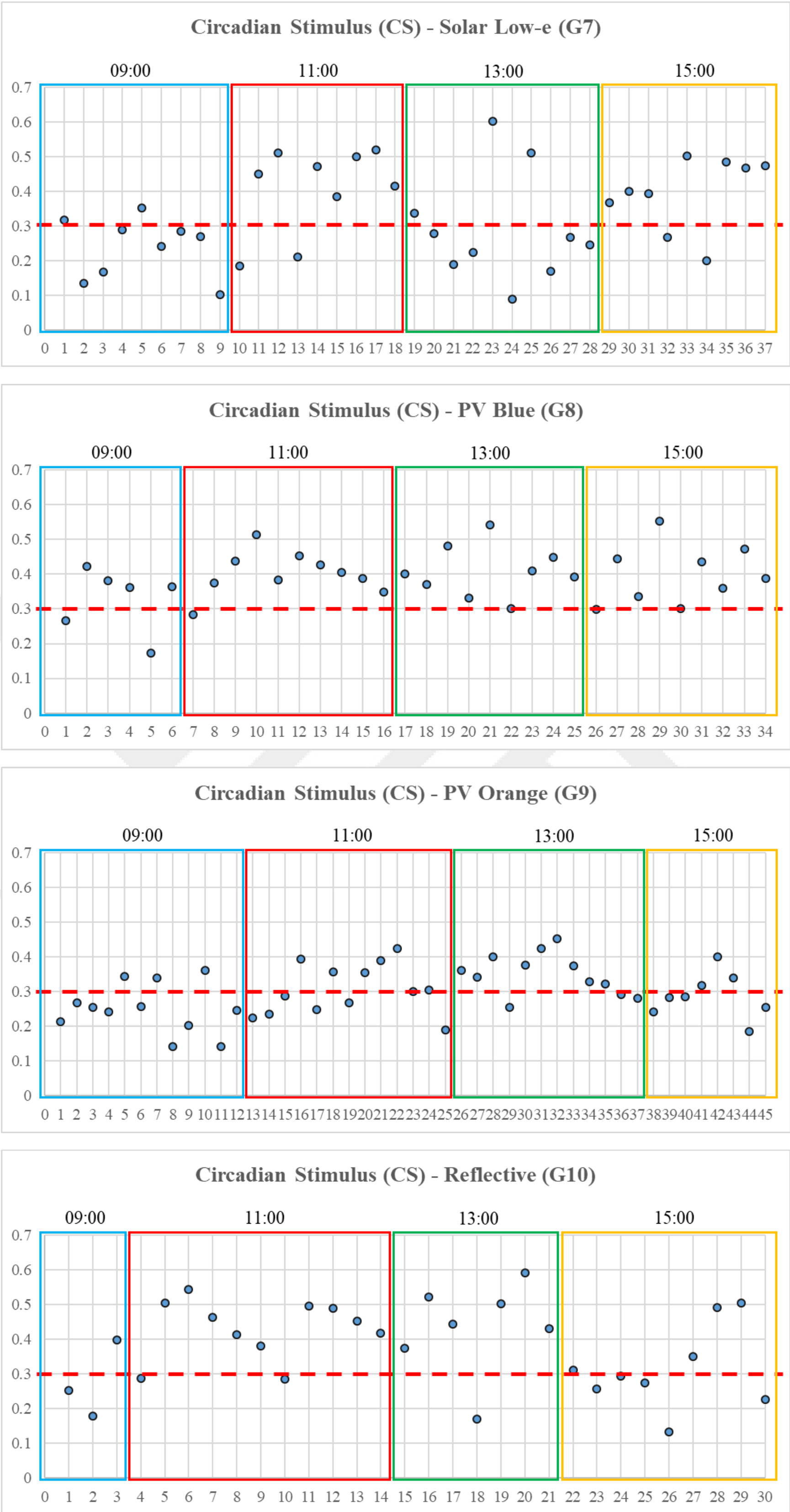
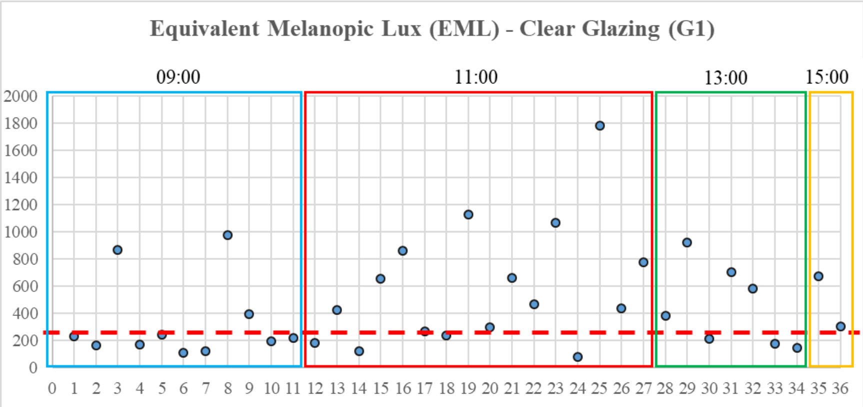


Figure 4.11. The distribution of CS values by time for various glass types


Equivalent Melanopic Lux (EML) - Clear Glazing (G1)
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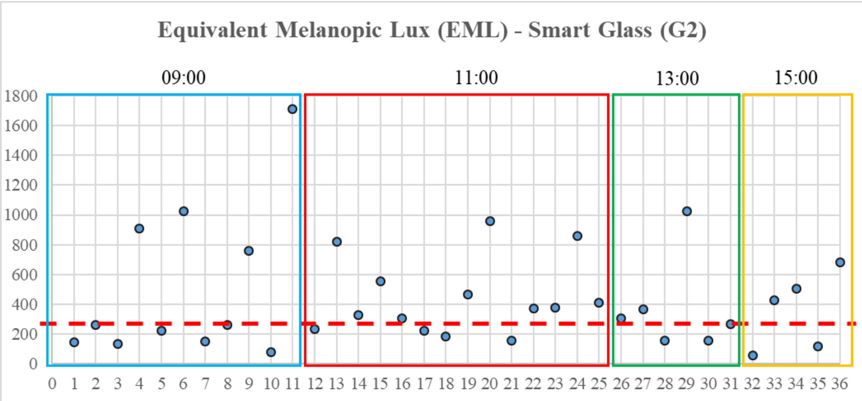
11:00
13:00
15:00
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36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13:00
15:00
1800
1600
1400
1200
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600
400
200
0
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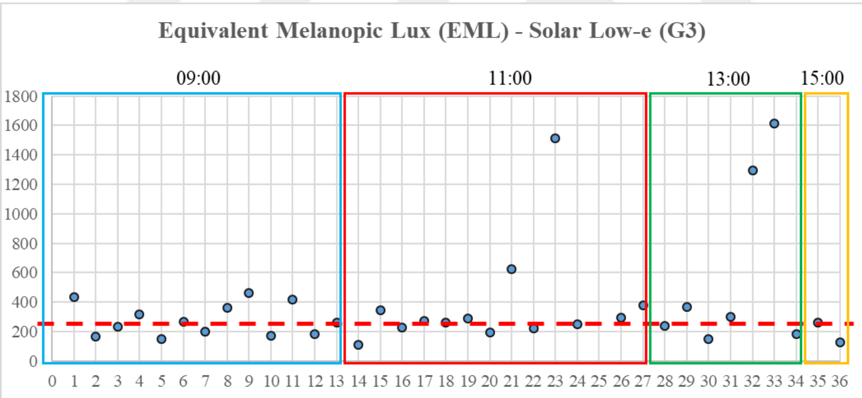
Equivalent Melanopic Lux (EML) - Solar Low-e (G3)
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11:00
13:00
15:00
1800
1600
1400
1200
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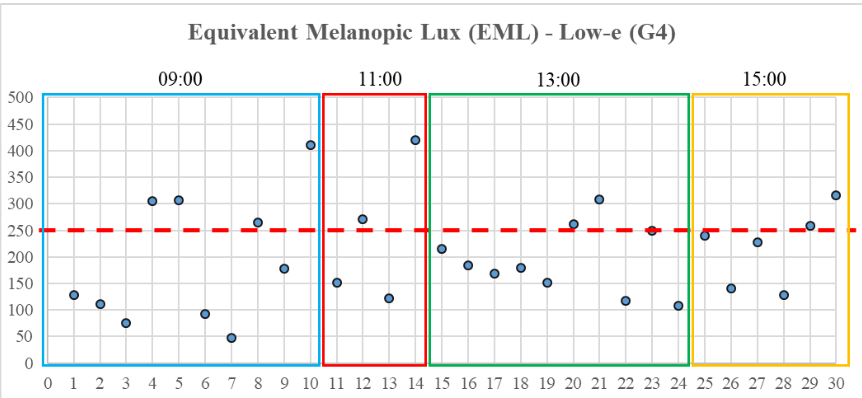
Equivalent Melanopic Lux (EML) - Low-e (G4)
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11:00
13:00
15:00
500
450
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350
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250
200
150
100
50
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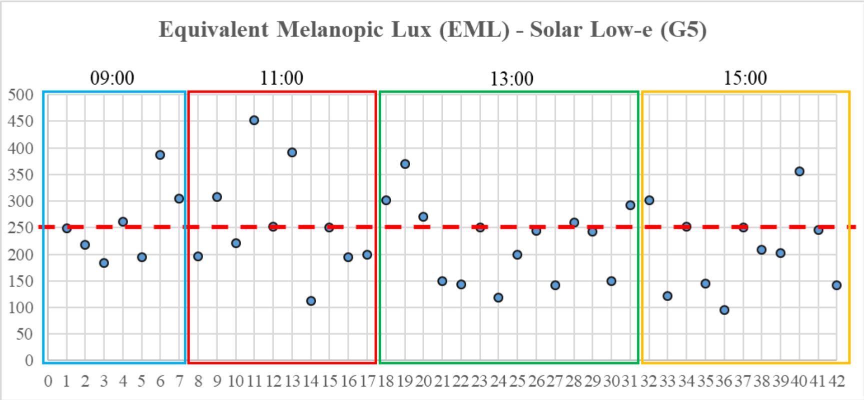
Equivalent Melanopic Lux (EML) - Solar Low-e (G5)
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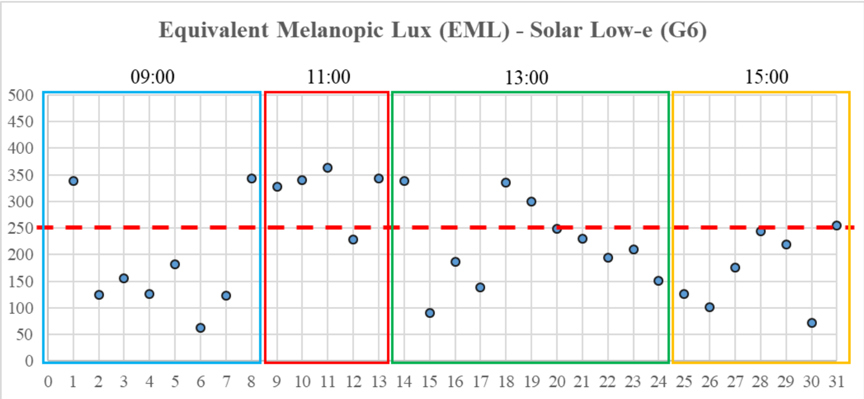
11:00
13:00
15:00


Equivalent Melanopic Lux (EML) - Solar Low-e (G6)
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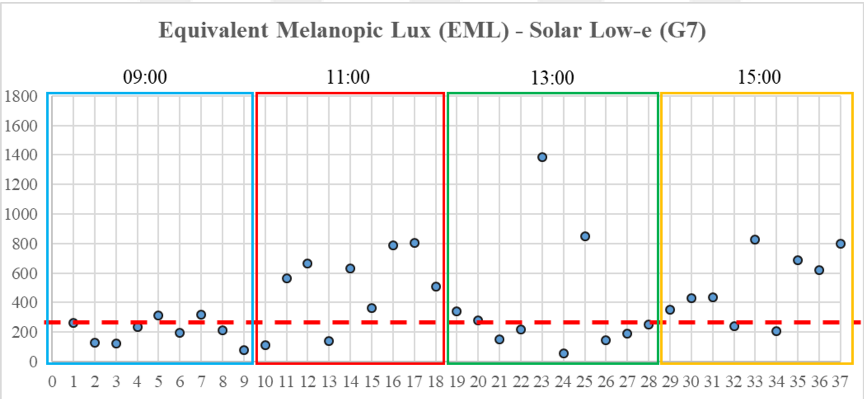
11:00
13:00
15:00


Equivalent Melanopic Lux (EML) - Solar Low-e (G7)
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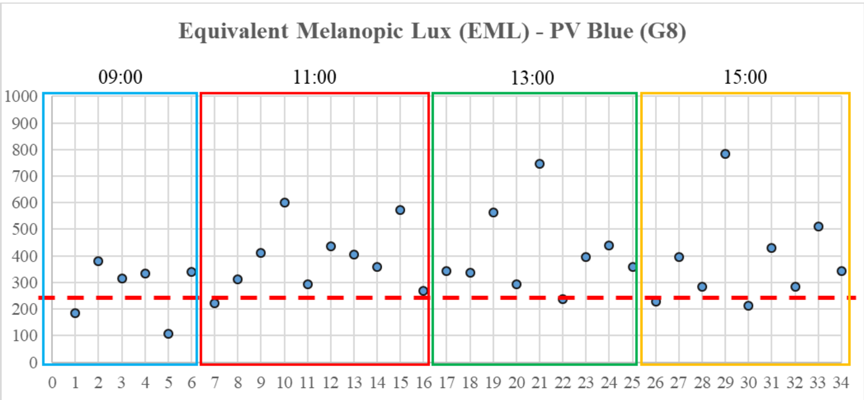
11:00
13:00
15:00


Equivalent Melanopic Lux (EML) - PV Blue (G8)
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11:00
13:00
15:00

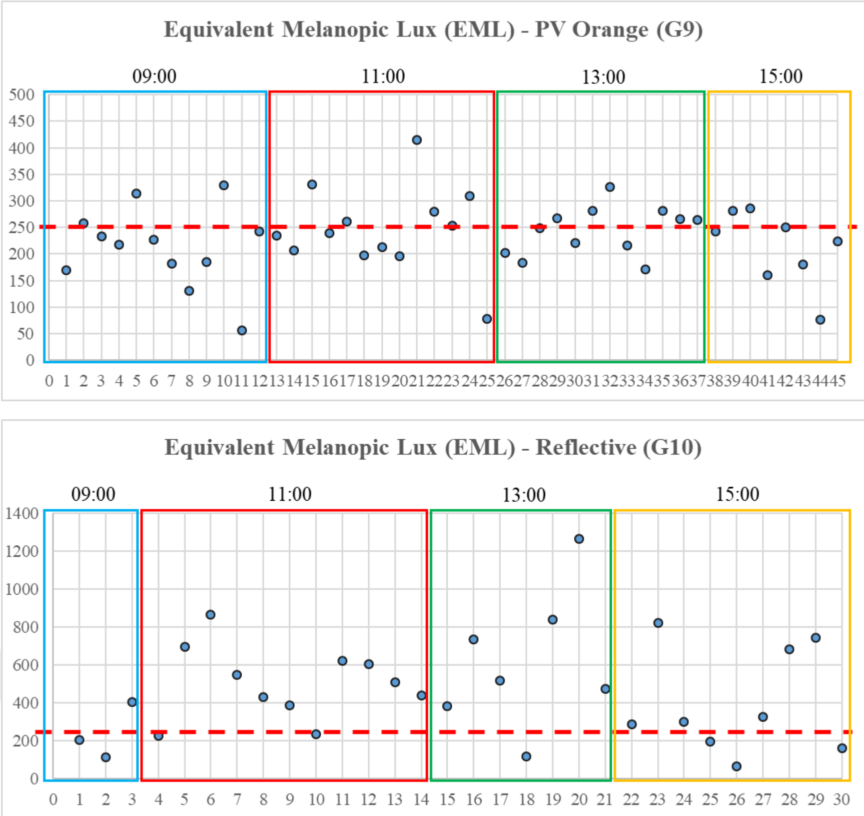


Figure 4.11. The distribution of EML values by time for various glass types

The values in Table 4.4 compare CS and EML values across different glass types in both the first and second stages of the experiment. Considering the threshold values of 0.3 for CS and 250 lux for EML, which are critical for ensuring sufficient circadian impact for health and performance, several key observations can be made. In the first stage, only three glass types (G1 and G2) reached or exceeded the CS threshold of 0.3. However, in the second stage, after the introduction of dynamic LED lighting, several glass types (G3, G7, G8, G9, G10) achieved this threshold, with G9 showing the most significant improvement in CS from 0.10 to 0.30. This indicates that dynamic lighting conditions helped elevate circadian stimulus values across many glass types, particularly those with lower initial values. For EML, the first stage shows that only four glass types (G1, G2, G7, and G10) exceeded the 250 lux threshold. With dynamic LED lighting in the second stage, nearly all glass types, except for G4 and G6, surpassed this threshold. The most notable improvements were observed in G3 (EML increased from 265 to 437) and G9 (from 38 to 231), showing significant enhancement in EML values.

These results underscore the positive effect of dynamic LED lighting in achieving required circadian light levels. The use of dynamic lighting in the second stage allowed for more glass types to meet the minimum required thresholds for CS and EML. Glasses that performed poorly under daylight (such as G4 and G9) showed considerable improvements under dynamic lighting, particularly in circadian effectiveness. Thus, it can be concluded that the transmittance and color characteristics of the glass significantly influence circadian indicators, and dynamic LED lighting can effectively boost circadian stimulus and melanopic lux to meet health and attention-related thresholds.

Table 4.4. Mean CS and EML values across different glass types

Glass Type	**Stage 1**		**Stage 2**	
	CS	**EML**	**CS**	**EML**
G1	**0,40**	**471**	0,36	**479**
G2	**0,40**	452	0,35	443
G3	0,29	265	0,33	437
G4	0,16	95	**0,24**	**205**
G5	0,17	98	0,28	233
G6	0,19	113	0,26	215
G7	0,24	220	0,33	403
G8	0,27	192	**0,39**	374
G9	**0,10**	**38**	0,30	231
G10	0,29	368	0,38	461

4.1.3. Task Performances and Subjective Evaluations

This section presents the results of the task performances and subjective evaluations conducted with participants under various lighting conditions. Descriptive statistics were used to summarize the data, highlighting the central tendencies and variations observed in the participants' responses. Accompanying graphical representations provide a visual summary of these findings, offering insights into how task performance and subjective assessments vary across the experimental stages under changing lighting conditions.

The data were analysed by categorizing them according to the room orientation (south/north), the stage of the experiment (default/preferred lighting), and the glass types. Figure 4.12 summarizes the general information for a total of 736 experiments and 368 participants. According to this, an almost equal number of experiments were conducted in rooms facing north and south. The academic and administrative staff of the faculty of architecture, mostly students, participated in the experiments. Although the participants did not have any mental or physical disorders to perform the experimental tasks, half reported eye conditions such as myopia or hyperopia. However, those who do not use any visual elements are in the majority. The time distribution of the experiments is almost the same. The majority of the experiments were carried out on clear and intermediate sky days. An intolerable sensation of visual discomfort was not reported in any of the experiments, indicating that there is no significant glare problem in both the default and preferred lighting settings.

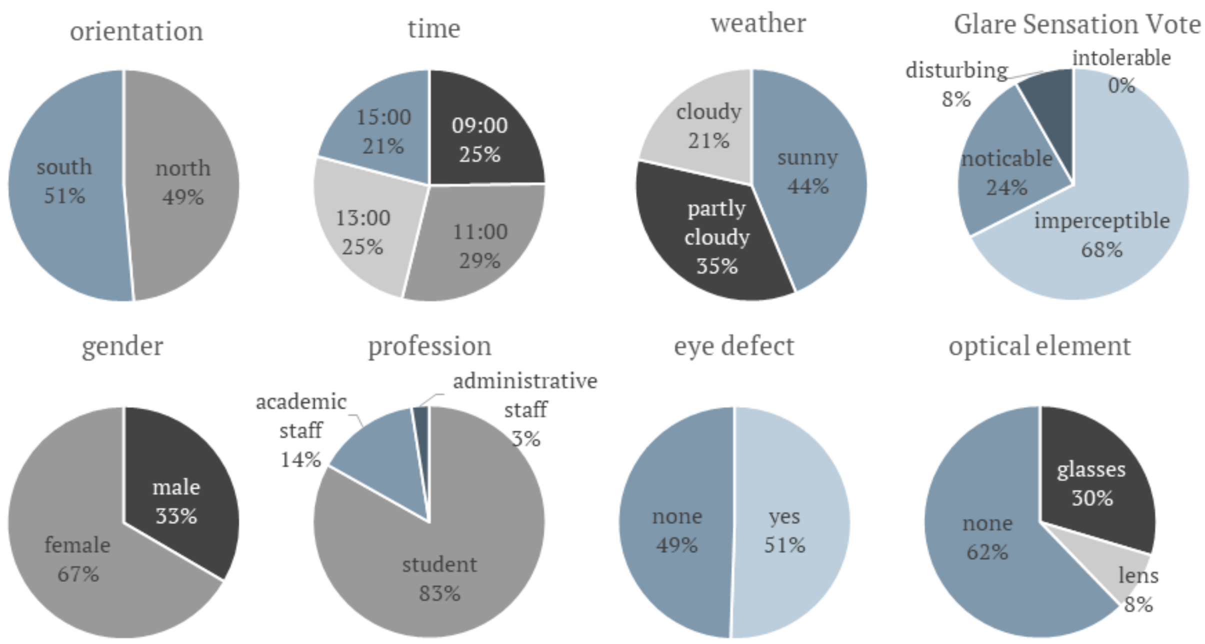


Figure 4.12. Summary of collected data including 368 participants and 736 experiments

The subjective ratings provided by participants on the Karolinska Sleepiness Scale (KSS), applied at the beginning and end of each lighting condition, were evaluated using a Likert scale ranging from 1 (most alert) to 9 (most sleepy). When considering all the data, the initial average KSS score was 3.58, while the final average score was 3.59. Although the difference between these averages is minimal, the distribution of scores at the beginning and end of each stage suggests that the characteristics of the lighting environment may have either a positive or negative effect on sleepiness. When comparing KSS results across experimental stages, the initial average KSS score in the first stage was 3.90, increasing slightly to 4.00 by the end of the stage. Although the difference in averages is not significant, the distribution of scores suggests that the lighting conditions in this stage may have contributed to an increase in sleepiness. In contrast, during the second stage, the initial average KSS score was 3.25, which decreased to 3.13 by the end, indicating that the lighting conditions in this stage may have had the opposite effect, enhancing alertness. The distribution of KSS scores at the beginning and end of each stage is presented in Figure 4.13.

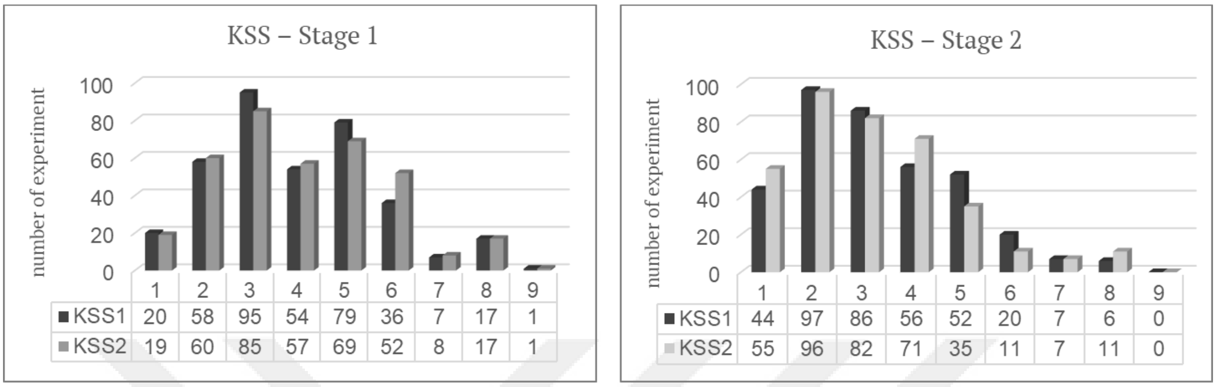


Figure 4.13. Distribution of KSS scores on a 9-point Likert scale

Positive and Negative Affect Schedule (PANAS) test was similarly administered to participants at the beginning and end of each lighting condition. The PANAS, consisting of 20 items, is divided into two scales: Positive Affect (PA) and Negative Affect (NA), each assessed using a 5-point Likert scale. Participants rated 10 positive and 10 negative adjectives to evaluate their mood and emotions under the specific lighting conditions. The PA score, ranging from 10 to 50, reflects the intensity of positive emotions, with higher scores indicating greater enthusiasm, energy, and alertness. Conversely, the NA score, also ranging from 10 to 50, measures the intensity of negative emotions, with higher scores indicating increased distress, anger, and nervousness. When all data are considered, participants' initial Positive Affect (PA) score averaged 30, while the Negative Affect (NA) score averaged 12. At the end of the experiment, the emotional states showed little change, with average scores of PA = 29 and NA = 12. It can be stated that there was no significant change in the participants' emotional states due to the lighting conditions they experienced. In the first stage, under default lighting settings, the PA score was lower, and the NA score was higher. However, in the second stage, where participants adjusted the lighting settings themselves, the PA score increased, and the NA score decreased. The average Positive and Negative Affect scores for each stage are presented in Figure 4.14.

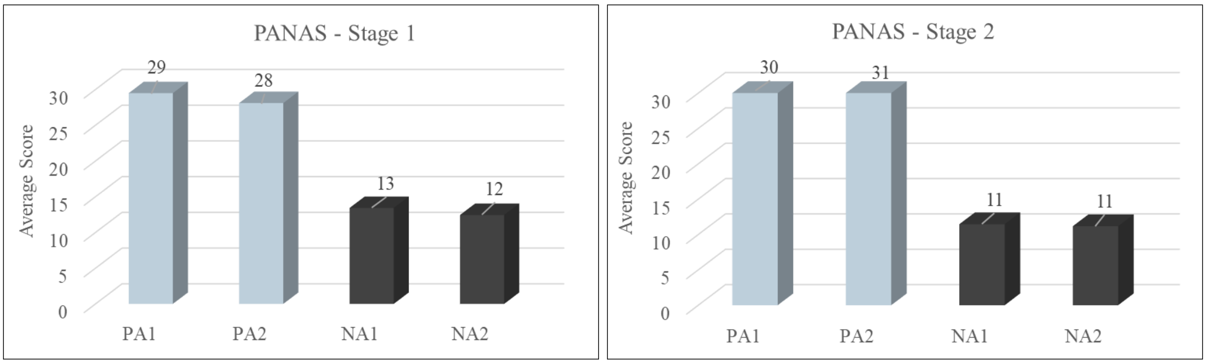


Figure 4.14. Average PA and NA scores

The Landolt test was used to assess participants' visual acuity, specifically the clarity or sharpness of vision, under varying lighting conditions. Performance was measured based on accuracy and errors. The number of rings counted in each direction by participants was compared to the actual number on the test sheet. The error rate reflects the proportion of incorrect responses relative to the total number of rings that participants were asked to count. Results indicate that the error rate decreased in the second stage of the experiment (Table 4.6). The highest error rate was observed with the solar low-e glass (G4), while the lowest was recorded with clear glass (G1) (Table 4.5).

In the Stroop test conducted on a computer, participants' cognitive interference and attention were assessed. The test involved presenting color words on the screen, with each word either matching (e.g., the word "red" displayed in red color) or mismatching (e.g., the word "red" displayed in green color) the actual color of the text. Response times were recorded for both congruent and incongruent conditions. In this context, a longer reaction time in the incongruent condition, where there is a mismatch between the word and the color, is expected. This longer reaction time reflects the cognitive interference caused by the conflicting information. Conversely, shorter reaction times in the congruent condition indicate that the participant was able to quickly and accurately process the information when there was no conflict between the word and color. The Stroop score is calculated as the difference between reaction times in the incongruent and congruent conditions (incongruent - congruent). A higher Stroop score signifies greater difficulty in processing the incongruent information, while a lower score indicates more efficient cognitive processing and fewer difficulties in dealing with conflicting information under specific lighting conditions. Table 4.6 presents the average reaction times in the first and second stages of the experiment. Results indicate that the reaction time, including incongruent and congruent conditions, decreased in the second stage. This reduction in reaction times suggests improved performance under preferred lighting settings. The results indicate that among the various glass types, the longest reaction times were observed with orange PV glass (G8), whereas the shortest reaction times were recorded with solar low-e glass (G4) (Table 4.5).

The n-back test conducted on the computer assessed participants' short-term memory and attention. In this test, participants were shown a series of letters over three phases, with the first phase serving as a practice session. Participants were required to click the mouse if the letter displayed on the screen matched the one shown two letters previously. Performance was evaluated based on the rates of correct matches, incorrect matches, and missed responses (i.e., responses that were not provided within the allotted time) in the final phase of the n-back test. A higher rate of correct matches indicates better performance. Results showed that, while the correct match rate increased in the second stage compared to the first stage of the experiment, the improvement was not substantial (Table 4.6). Among the different glass types, solar low-e glass (G4) facilitated the best performance, similar to the Stroop test results. Conversely, the lowest correct match rate was observed with low-e (G3) and blue solar low-e glass (G6) (Table 4.5).

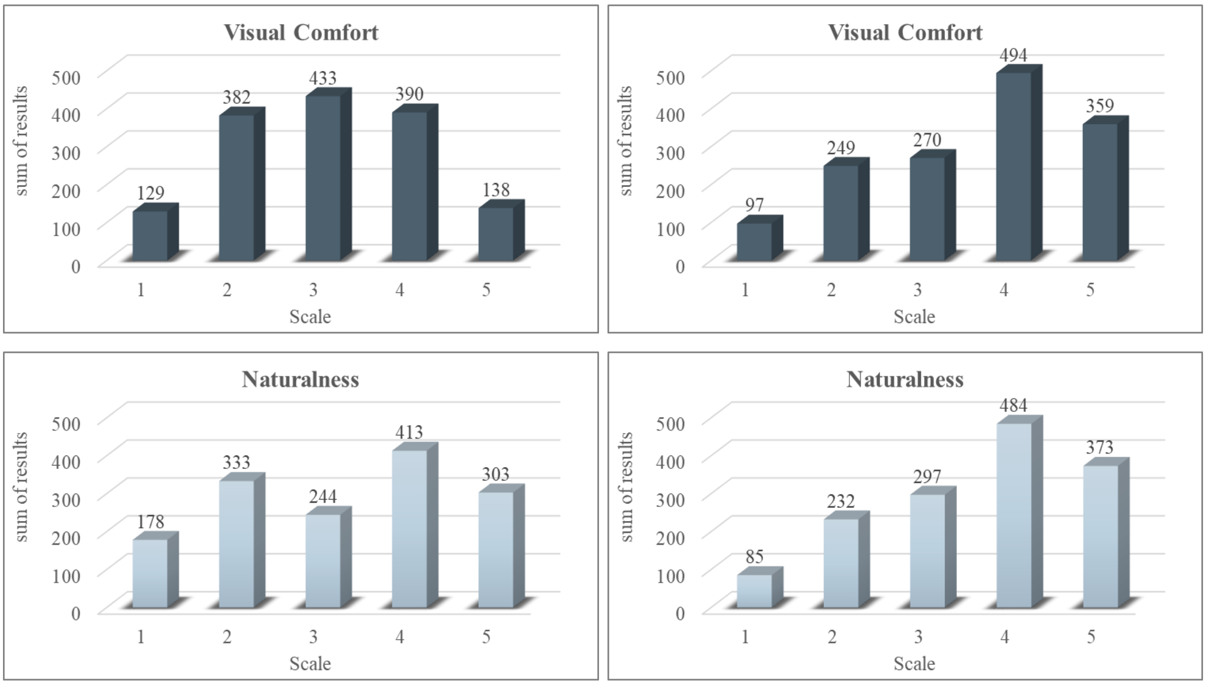
Table 4.5. Performance test results based on glass types

Glass type	landolt	Stroop Test			N-back Test		
	error rate (%)	incongruent (ms)	congruent (ms)	Stroop score (ms)	correct match (%)	missed match (%)	false match (%)
G1	**23**	935	868	67	74	18	3
G2	26	906	818	88	75	17	1
G3	26	933	833	100	**69**	**23**	3
G4	**50**	**883**	**772**	111	**78**	**13**	3
G5	30	933	851	82	77	16	3
G6	32	925	841	78	**69**	**22**	3
G7	32	953	**883**	70	72	19	3
G8	31	**960**	855	105	71	19	3
G9	32	954	865	89	71	19	3
G10	49	944	860	84	78	15	2

Table 4.6. Performance test results based on experimental stages

	Landolt	Stroop			N-back		
	error rate (%)	incongruent (ms)	congruent (ms)	Stroop score (ms)	correct match (%)	missed match (%)	false match (%)
Stage 1	37	1004	919	85	72	20	3
Stage 2	29	863	773	90	75	16	3

The comprehensive questionnaire, designed around the terms (1) Visual Comfort, (2) Naturalness, (3) Precision (details and textures), and (4) Satisfaction, assessed participants' perceptions of lighting conditions across different stages of the experiment. The written questionnaire utilized a five-point Likert scale with semantic opposites, where ratings closer to 5 reflect more positive evaluations and those closer to 1 indicate more negative perceptions. Figure 4.15 illustrates the sum of ratings for each question group, offering insights into how participant responses shifted between the first and second stages of the experiment. This visualization helps in understanding the impact of different lighting scenarios on user experiences, as reflected in the questionnaire responses. The improvements across the board from stage 1 to stage 2 suggest that lighting conditions in the second stage were more favorable for participants, likely due to adjustments made to enhance visual comfort and satisfaction using dynamic LED lighting.



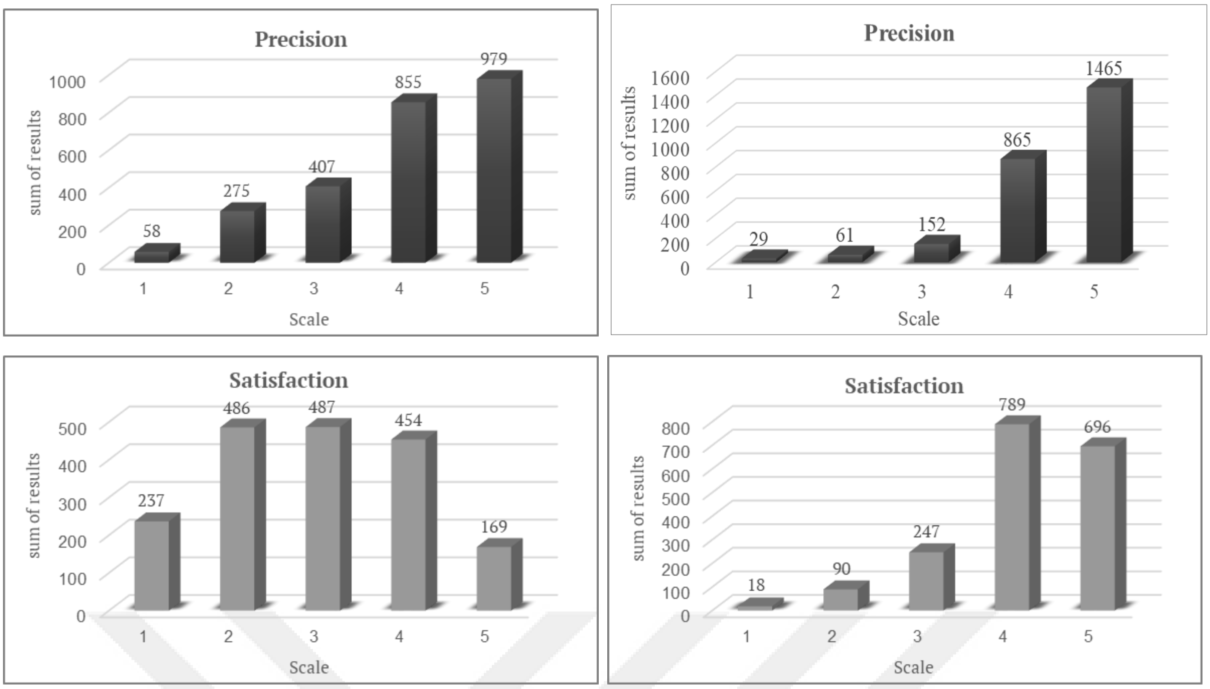


Figure 4.15. Ratings on a 5-point Likert Scale for each question group in the first (left) and second (right) stage of the experiment

The results from both the first and second stages of the experiment are summarized in Table 4.7, which shows the cumulative ratings for each glass type across these evaluative categories. Despite the expectation that the use of dynamic LED lighting in the second stage would result in more positive questionnaire responses, the results indicate which glass types exhibited the most pronounced changes. Clear glass (G1), solar low-e glass (G4), and bronze solar low-e glass (G7) appear to be the highest-performing glass types in both stages across all categories. These types consistently show improved comfort, naturalness, precision, and satisfaction in the second stage, indicating they were well-received overall. Orange PV (G8) and blue PV (G9) glasses, however, initially had the lowest ratings across most categories, particularly naturalness and satisfaction. Although there were improvements in second stage, these glass types still performed less favorably compared to others. This observation suggesst that during the initial stage based solely on daylight, the lighting conditions provided by G8 and G9 glasses were perceived as artificial or unnatural, resulting in lower satisfaction levels. However, in the second stage, the introduction of artificial lighting improved these perceptions to some extent, leading to a noticeable increase in satisfaction.

Table 4.7. Mean ratings for four question groups: Visual Comfort (com.), Naturalness (nat.), Precision (Prec.), and Satisfaction

Glass Type	**Stage 1**				**Stage 2**			
	Com.	**Nat.**	**Prec.**	**Sat.**	**Com.**	**Nat.**	**Prec.**	**Sat.**
G1	11.81	14.96	31.68	17.18	14.72	16.51	32.04	21.69
G2	11.83	13.08	29.47	16.08	14.42	15.06	31.47	20.92
G3	12.08	13.08	29.03	15.85	13.69	15.26	30.28	19.51
G4	12.69	14.06	27.63	15.19	15.44	15.25	31.75	21.88
G5	12.02	13.49	27.28	15.09	13.88	13.51	30.95	20.58
G6	11.77	14.03	29.61	15.42	14.06	14.03	31.88	20.13
G7	12.32	14.78	30.51	15.54	14.65	14.81	32.78	21.76
G8	12.91	7.29	23.06	11.26	13.68	12.29	29.35	20.09
G9	11.80	10.47	23.06	11.29	13.29	12.44	29.53	19.56
G10	11.60	14.20	25.51	13.06	13.51	13.83	30.49	20.09

4.2. Statistical Analysis

4.2.1. Correlation Analysis and Scatterplots

Correlation analyses were conducted to explore the relationships between performance indicators and the measurable physical lighting parameters for each type of glass. These analyses were visually represented through scatterplots and the corresponding R-squared values. Figure 3.9 presents the performance tests and lighting measurements included in the correlation analysis. Table 4.8 presents the correlation coefficients between task performance and mood indicators (PANAS) and lighting parameters for each glass type. The strength of these relationships was determined based on Pearson's correlation coefficient (r), where values between 0.1-0.3 indicate a weak relationship, 0.3-0.5 suggest a moderate relationship, and values greater than 0.5 denote a strong relationship (Pearson 1895; Yıldız 2018). The correlation coefficients were colored according to the degree of relationship for clarity in interpretation.

In the correlation analysis, no significant or strong correlations were observed between performance tests and lighting measurements for clear glass (G1), smart glass (G2), and neutral solar low-e glass (G4). However, for low-e glass (G3), a moderate inverse correlation was found between short-term memory test (n-back) results and lighting and circadian parameters. Specifically, as illuminance and circadian values increased, the correct match rate in the n-back test decreased. For smoked solar low-e glass (G5), workplane CCT was found to be correlated with reaction time in the Stroop test and mood parameters. An increase in workplane CCT was associated with an increase in positive mood and a decrease in negative mood. Additionally, higher CCTs corresponded with faster response times in the Stroop test. When using blue solar low-e glass (G6), Stroop test response times showed an inverse and relatively stronger correlation with all illuminance parameters compared to other glass types, indicating that as illuminance, color temperature, CS, and EML increased, response times decreased. Similarly, negative mood were also inversely affected, showing a decrease. For bronze solar low-e glass (G7), performance was not influenced by lighting parameters, but negative mood exhibited a similar correlation to that seen with G6. When using Blue PV Glass (C8), the entire room appears in shades of blue. All lighting measurements, except SPD, linearly affect Landolt error rates and Stroop response times, showing stronger correlations (r=0.24-0.55) than other glass types. Increased illuminance, CS, and EML result in fewer errors on the Landolt test, with workplane illuminance having the highest correlation (0.55). Higher CCTs lead to more errors, likely due to the predominant blue tint observed during the first stage of the experiment, when only daylight was present. Stroop test response times are similarly affected. Unlike other glass types, higher illuminance, CS, and EML improve mood, increasing positive affect and decreasing negative affect. Figure 4.16 illustrates scatterplots for the strongest correlations observed, highlighting the direction and magnitude of the relationships between variables, as measured by Pearson's correlation coefficient (r). With Orange PV Glass (C9), performance parameters show strong linear correlations with lighting measurements, but in an inverse manner. Increased illuminance, CCT, CS, and EML lead to fewer errors on the Landolt test and shorter Stroop test response times. Correct responses in the N-back test increase, while errors decrease. As illuminance and CCT rise (cool white), negative affect diminishes, and positive affect rises. The dominant orange hue of the glass may have been balanced by dynamic LED lighting, enhancing its positive impact. For Reflective Glass (C10), a moderate correlation exists between eye-level illuminance, EML, and mood indicators, with increased values improving positive mood.

Table 4.8. Correlation coefficients between task performance, mood, and lighting parameters across glass types

G1	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.02	0.07	0.07	0.05	0.01	0.06	0.13	0.00	0.03
incongurent	0.10	0.10	0.02	0.08	0.16	0.09	0.04	0.01	0.08
congurent	0.05	0.20	0.13	0.06	0.25	0.24	0.05	0.05	0.02
stroop	0.08	0.21	0.22	0.03	0.20	0.30	0.02	0.11	0.13
correct	0.25	0.13	0.21	0.10	0.08	0.14	0.10	0.27	0.24
missed	0.13	0.06	0.17	0.02	0.00	0.10	0.04	0.18	0.13
false	0.04	0.01	0.02	0.06	0.08	0.02	0.11	0.04	0.04
PA1	0.03	0.05	-0.04	0.05	0.06	-0.11	0.04	0.05	0.02
NA1	-0.22	-0.07	0.11	-0.13	0.04	0.00	-0.06	-0.15	-0.21
PA2	0.11	0.03	-0.05	0.12	0.02	-0.10	0.15	0.09	0.10
NA2	-0.19	-0.04	0.12	-0.12	0.08	0.02	-0.07	-0.11	-0.19

G2	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.10	-0.05	-0.08	-0.08	-0.19	0.17	-0.11	0.12	0.10
incongruent	-0.06	0.14	-0.07	-0.12	0.04	-0.03	-0.16	0.08	-0.04
congruent	-0.02	0.23	-0.16	-0.13	0.14	-0.12	-0.19	0.16	0.01
stroop	-0.05	-0.17	0.14	0.04	-0.15	0.15	0.07	-0.14	-0.07
correct	0.07	0.08	-0.12	0.12	0.08	-0.17	0.13	0.05	0.06
missed	-0.05	-0.14	0.17	-0.08	-0.15	0.18	-0.04	-0.04	-0.06
false	0.08	0.18	0.01	-0.07	0.14	-0.11	-0.19	0.08	0.12
PA1	0.13	-0.11	0.04	0.27	-0.13	-0.16	0.26	0.23	0.10
NA1	-0.08	0.19	-0.07	-0.14	0.21	-0.02	-0.20	-0.03	-0.04
PA2	0.15	-0.06	0.03	0.30	-0.04	-0.19	0.29	0.22	0.14
NA2	-0.03	0.16	-0.06	-0.13	0.15	-0.06	-0.20	0.00	0.00

G3	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.19	0.10	-0.07	0.18	0.10	-0.03	0.15	0.20	0.21
incongruent	-0.02	0.01	-0.11	-0.04	0.02	-0.13	-0.04	0.12	0.00
congruent	0.07	0.06	-0.15	0.05	0.06	-0.17	0.02	0.19	0.10
stroop	-0.17	-0.10	0.09	-0.16	-0.06	0.07	-0.11	-0.14	-0.19
correct	-0.36	0.03	-0.04	-0.32	0.07	-0.12	-0.28	-0.31	-0.38
missed	0.40	-0.01	0.01	0.34	-0.05	0.09	0.30	0.30	0.42
false	-0.05	-0.06	0.00	0.01	-0.10	0.10	0.04	-0.16	-0.05
PA1	0.08	-0.12	0.21	0.15	-0.04	-0.01	0.20	0.07	0.07
NA1	-0.11	0.07	-0.04	-0.13	0.04	-0.01	-0.12	-0.07	-0.10
PA2	0.01	-0.06	0.12	0.10	0.03	-0.10	0.12	0.09	0.00
NA2	-0.09	-0.04	0.08	-0.09	-0.07	0.13	-0.07	-0.09	-0.09

G4	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.08	0.04	-0.06	0.07	0.14	-0.20	0.08	0.08	0.09
incongruent	-0.14	-0.16	0.16	-0.13	-0.18	0.13	-0.15	-0.18	-0.19
congruent	-0.17	-0.17	0.14	-0.17	-0.19	0.14	-0.19	-0.20	-0.21
stroop	0.02	-0.01	0.05	0.05	-0.01	-0.02	0.06	0.03	0.02
correct	0.21	0.17	-0.17	0.15	0.08	-0.07	0.17	0.21	0.26
missed	-0.24	-0.20	0.20	-0.20	-0.14	0.15	-0.20	-0.26	-0.27
false	-0.06	-0.06	0.12	-0.01	0.00	0.12	-0.03	-0.08	-0.08
PA1	0.25	0.12	-0.04	0.26	0.11	-0.04	0.25	0.26	0.25
NA1	-0.18	-0.18	0.09	-0.16	-0.19	0.04	-0.17	-0.16	-0.22
PA2	0.21	0.03	0.05	0.24	0.07	-0.03	0.22	0.19	0.16
NA2	-0.02	0.02	0.00	0.03	0.03	-0.08	0.01	0.00	-0.03

G5	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	-0.22	-0.16	0.04	-0.16	-0.12	-0.08	-0.15	-0.16	-0.21
incongruent	-0.10	-0.18	-0.14	-0.16	-0.33	0.02	-0.15	-0.03	-0.10
congruent	-0.15	-0.25	-0.07	-0.21	-0.35	0.04	-0.20	-0.07	-0.17
stroop	0.09	0.11	-0.14	0.09	0.02	-0.04	0.09	0.07	0.12
correct	-0.13	-0.09	0.11	-0.12	-0.06	0.12	-0.12	-0.03	-0.13
missed	0.11	0.14	-0.15	0.09	0.10	-0.12	0.09	0.04	0.14
false	-0.02	0.01	0.09	-0.03	0.02	0.09	-0.02	-0.04	-0.01
PA1	0.02	0.07	0.05	0.02	0.21	-0.04	0.05	0.09	0.04
NA1	-0.15	-0.07	-0.12	-0.21	-0.19	0.05	-0.24	-0.08	-0.14
PA2	0.08	0.20	0.01	0.10	0.31	-0.10	0.12	0.17	0.12
NA2	-0.11	-0.11	-0.06	-0.17	-0.25	0.13	-0.20	-0.04	-0.12

G6	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	-0.14	-0.16	0.14	-0.04	-0.09	0.03	-0.06	-0.05	-0.15
incongruent	-0.46	-0.30	0.15	-0.38	-0.24	0.10	-0.43	-0.28	-0.45
congruent	-0.45	-0.38	0.24	-0.41	-0.35	0.22	-0.44	-0.36	-0.47
stroop	-0.08	0.08	-0.01	-0.05	0.13	-0.12	-0.08	0.07	-0.04
correct	0.04	0.11	-0.01	0.03	0.15	-0.04	0.03	0.17	0.07
missed	-0.04	-0.11	0.03	-0.04	-0.12	0.08	-0.05	-0.15	-0.07
false	0.07	0.07	-0.05	0.10	-0.01	0.01	0.07	0.18	0.10
PA1	0.20	0.17	-0.10	0.08	0.05	-0.04	0.09	0.14	0.21
NA1	-0.29	-0.24	0.19	-0.27	-0.19	0.17	-0.27	-0.12	-0.29
PA2	0.07	0.16	-0.23	0.10	0.15	-0.17	0.09	0.05	0.10
NA2	0.04	0.00	0.14	-0.11	-0.13	0.12	-0.08	0.14	0.05

G7	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.07	0.07	-0.18	-0.04	-0.02	-0.09	-0.07	0.02	0.08
incongruent	0.03	0.11	-0.23	-0.04	0.01	-0.07	0.00	0.02	0.04
congruent	-0.02	0.12	-0.31	-0.08	0.00	-0.15	-0.06	-0.03	0.00
stroop	0.09	-0.04	0.16	0.08	0.02	0.13	0.11	0.08	0.07
correct	0.02	0.10	-0.09	0.01	0.06	-0.02	0.00	-0.03	0.01
missed	-0.03	-0.08	0.03	-0.03	-0.05	0.00	0.01	0.00	-0.02
false	-0.01	-0.03	0.03	-0.01	-0.05	0.05	-0.07	0.00	-0.01
PA1	0.17	0.01	0.13	0.11	0.04	0.07	0.12	0.14	0.15
NA1	-0.19	0.23	-0.53	-0.24	0.09	-0.29	-0.21	-0.25	-0.18
PA2	0.18	-0.02	0.19	0.10	0.02	0.12	0.11	0.13	0.16
NA2	-0.17	0.38	-0.74	-0.22	0.21	-0.45	-0.19	-0.20	-0.15

G8	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	-0.49	0.37	-0.16	-0.56	0.37	-0.06	-0.47	-0.38	-0.41
incongruent	-0.37	0.38	-0.09	-0.37	0.38	-0.16	-0.39	-0.21	-0.24
congruent	-0.40	0.37	-0.06	-0.40	0.35	-0.15	-0.41	-0.30	-0.31
stroop	0.14	-0.07	-0.04	0.13	-0.02	0.00	0.11	0.21	0.17
correct	0.08	-0.17	-0.10	0.08	-0.16	0.06	0.09	0.14	0.12
missed	-0.09	0.20	-0.03	-0.10	0.20	-0.15	-0.12	-0.06	-0.05
false	-0.06	0.16	0.14	-0.13	0.18	0.12	-0.09	-0.09	-0.06
PA1	-0.24	-0.04	0.10	-0.11	-0.05	0.15	-0.10	-0.41	-0.43
NA1	-0.32	0.22	-0.06	-0.32	0.23	0.00	-0.31	-0.24	-0.26
PA2	0.01	-0.25	0.22	0.08	-0.26	0.28	0.12	-0.26	-0.22
NA2	-0.21	0.25	-0.06	-0.24	0.25	-0.08	-0.21	-0.16	-0.14

G9	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	-0.38	-0.21	0.16	-0.38	-0.24	0.11	-0.32	-0.38	-0.32
incongruent	-0.36	-0.26	0.12	-0.36	-0.28	0.13	-0.38	-0.31	-0.33
congruent	-0.39	-0.31	0.17	-0.39	-0.33	0.19	-0.44	-0.37	-0.38
stroop	0.09	0.10	-0.08	0.10	0.10	-0.10	0.15	0.15	0.11
correct	0.18	0.18	-0.23	0.21	0.17	-0.20	0.23	0.21	0.21
missed	-0.23	-0.30	0.31	-0.24	-0.30	0.27	-0.25	-0.24	-0.30
false	-0.01	-0.11	0.09	-0.03	-0.12	0.09	-0.01	-0.03	-0.06
PA1	0.04	0.03	0.00	0.04	0.02	0.04	0.01	0.09	0.02
NA1	-0.27	-0.26	0.20	-0.28	-0.27	0.19	-0.31	-0.26	-0.28
PA2	0.20	0.22	-0.15	0.22	0.22	-0.15	0.21	0.25	0.22
NA2	-0.12	-0.18	0.12	-0.17	-0.19	0.15	-0.20	-0.13	-0.16

G10	EV3	CCT3	SPD3	Ew	CCTw	SPDw	Eavg	CS	EML
landolt	0.01	-0.08	0.12	0.05	-0.04	-0.05	0.09	0.04	-0.01
incongruent	0.15	0.04	-0.19	-0.12	0.03	-0.13	-0.19	-0.05	0.16
congruent	0.15	0.08	-0.22	-0.12	0.06	-0.23	-0.22	-0.11	0.16
stroop	-0.02	-0.08	0.10	0.00	-0.07	0.25	0.11	0.16	-0.04
correct	0.09	-0.09	0.10	0.10	-0.07	0.11	0.13	0.18	0.08
missed	-0.03	0.10	-0.10	-0.11	0.05	-0.08	-0.13	-0.16	-0.02
false	-0.02	-0.21	0.13	0.26	-0.15	0.03	0.15	0.06	-0.03
PA1	0.39	-0.07	-0.02	0.21	-0.02	0.01	0.20	0.25	0.40
NA1	-0.06	0.07	-0.20	-0.12	0.15	-0.32	-0.11	-0.07	-0.05
PA2	0.24	-0.14	0.04	0.21	-0.11	0.12	0.23	0.18	0.23
NA2	-0.01	0.10	-0.15	-0.13	0.15	-0.30	-0.13	0.01	0.01

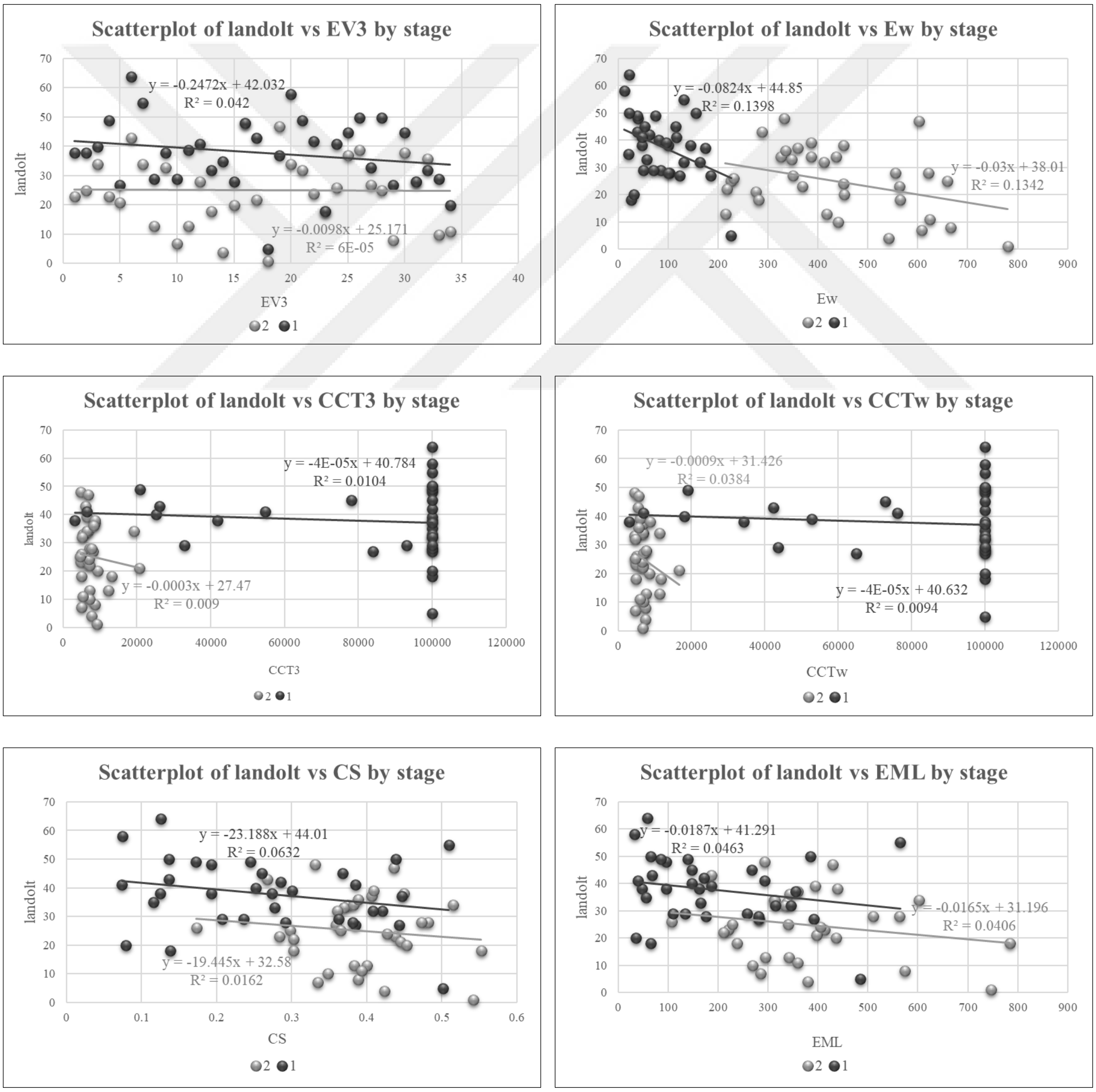


Figure 4.16. Scatterplots displaying the strongest correlations observed in Blue PV Glass

4.2.2. T-tests and ANOVA

The T-test was designed to compare the mean differences between two groups based on circadian lighting indicators: Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML). For this analysis, participants were grouped according to threshold values: one group included participants with CS values below 0.3 and EML values below 250 lux, while the other group consisted of those with CS values above 0.3 and EML values above 250 lux. These thresholds were chosen based on established guidelines indicating that a CS value of 0.3 and an EML value of 250 lux are necessary to achieve sufficient circadian stimulation to positively impact health and cognitive function. To assess the statistical significance of differences between these two groups, a two-tailed independent T-test was conducted. The p-value less than 0.01 indicates a highly significant difference; p-values between 0.01 and 0.05 suggest a significant difference; and p-values between 0.05 and 0.1 reflect marginal significance.

The T-test results indicate significant differences in lighting conditions when comparing mean values above and below the threshold for CS (0.3) and EML (250 lux), as reported in Table 4.9. For both parameters, higher values of CS and EML are associated with significantly greater illuminance across all measured variables, including eye-level (EV3) and workplane (Ew) illuminance, eye-level (CCT3) and workplane (CCTw) correlated color temperature, eye-level (SPD3) and wokplane (SPDw) dominant wavelength. Specifically, the mean illuminance are substantially higher when CS and EML exceed their respective thresholds, with p-values of 0.00 across the board. These results highlight that higher circadian stimulus and melanopic lux levels are strongly correlated with cooler, brighter lighting conditions, suggesting that specific lighting designs can more effectively meet circadian requirements.

The analysis of performance metrics shows mixed results. While significant differences are observed in the Landolt test, with error rates decreasing when CS and EML are above their respective thresholds ($p = 0.02$ and $p = 0.03$), no such significant differences are found for the Stroop and N-back tests. The Landolt test's significant results suggest that higher circadian and melanopic stimulus levels improve visual performance and accuracy, but the lack of notable differences in Stroop and N-back results implies that cognitive tasks like reaction time and memory recall may not be as strongly affected by variations in lighting conditions. Overall, while circadian lighting positively influences paper-based tasks, its effects on computer-based tasks require further exploration (Table 4.9).

In terms of subjective experiences, the results show significant improvements in participants' self-reported mood, comfort, and satisfaction under higher CS and EML conditions. Positive affect (PA2) increases significantly with CS > 0.3 ($p = 0.00$) and EML > 250 ($p = 0.01$), while negative affect (NA) decreases significantly ($p = 0.01$ and $p = 0.00$, respectively). Participants also report feeling visually more comfortable ($p = 0.00$) and satisfied ($p = 0.00$) under lighting conditions that exceed circadian thresholds. Additionally, perceptions of naturalness and precision improve significantly under higher CS and EML. These findings suggest that circadian-effective lighting not only enhances objective performance in certain tasks but also contributes to more positive emotional and psychological states, improving overall comfort and well-being (Table 4.9).

Table 4.9. T-Test results for differences in CS and EML across thresholds

	Circadian Stimulus (CS)			**Equivalent Melanopic Lux (EML)**		
	mean below 0.3	**mean above 0.3**	**p-value**	**mean below 250**	**mean above 250**	**p-value**
EV3	194.11	538.16	0.00***	186.79	549.47	0.00***
CCT3	4115.15	6007.01	0.00***	4124.87	6000.89	0.00***
SPD3	572.18	555.90	0.00***	571.74	556.35	0.00***
Ew	273.27	588.73	0.00***	262.45	604.28	0.00***
CCTw	4373.38	5880.84	0.00***	4502.09	5729.56	0.00***
SPDw	569.82	554.74	0.00***	569.18	555.46	0.00***
KSS1	3.68	3.48	0.10	3.72	3.43	0.02**
PA1	29.53	30.53	0.07*	29.602	30.45	0.13
NA1	12.76	12.03	0.01**	12.86	11.90	0.00***
Landolt	34.39	30.96	0.02**	34.30	31.05	0.03**
Stroop	939.196	926.570	0.35	941.578	923.52	0.18
N-back	72.966	74.131	0.41	73.083	73.99	0.52
Comfort	13.20	14.59	0.00***	13.16	14.65	0.00***
Naturalness	13.32	13.87	0.02**	13.22	14.00	0.00***
Precision	28.54	30.16	0.00***	28.51	30.21	0.00***
Satisfaction	16.34	19.02	0.00***	16.28	19.11	0.00***
KSS2	3.71	3.42	0.03**	3.75	3.37	0.00***
PA2	28.55	30.29	0.00***	28.59	30.25	0.01**
NA2	11.88	11.70	0.45	28.59	30.25	0.01**

Statistical significance levels: ***when p-value<0.01, **when 0.01< p-value < 0.05, *when 0.05 < p-value < 0.1

The ANOVA (analysis of variance) analysis conducted in this study was designed to investigate the impact of different light levels on various psychological and physiological responses. The illuminance was categorized into three distinct groups based on average horizontal illuminance throughout the room: illuminance below 300 lux (1), illuminance between 300 and 750 lux (2), and illuminance above 750 lux (3). These divisions were established to explore the effects of low, moderate, and high illuminance on participants' performance in cognitive and visual tasks, their subjective judgments, and circadian indicators.

The analysis shows a clear trend where higher illuminance correlate with increased CS and EML. Specifically, Group 3 (above 750 lux) demonstrates the highest mean values for both CS (0.45) and EML (673.52), suggesting that higher illuminance significantly enhances circadian effectiveness. The statistically significant p-values (0.00) indicate robust differences between the groups, affirming the impact of sufficient lighting on circadian health parameters.

Performance on visual and cognitive tasks shows improvement with increased illuminance. The Landolt test, which assesses visual acuity, shows lower error rates when illuminance is between 300-750 lux, with a significant difference noted (p=0.00). Similarly, the Stroop test, measuring cognitive processing speed, records faster response times in higher illuminance groups, particularly between the lowest and highest groups (p=0.00). However, the N-back test, aimed at evaluating working memory, does not exhibit significant differences across the groups (p=0.53), suggesting that memory performance might not be as influenced by changes in lighting conditions as other cognitive functions (Table 4.10).

Subjective evaluations across various dimensions consistently show significant improvements with increased illuminance. Notably, Karolinska Sleepiness Scale (KSS) scores significantly decreased (p=0.00) as illuminance levels rose, enhancing alertness in brighter environments. Positive affect saw a notable increase (p=0.036), while negative affect significantly decreased (p=0.00). Moreover, attributes such as comfort, naturalness, precision, and satisfaction all showed significant improvements (p=0.00), indicating that optimal lighting improves environmental perception and satisfaction. The Glare Sensation Vote (GSV) revealed that higher satisfaction with environmental conditions was correlated with higher illuminance levels, with lower GSV scores denoting greater comfort against potential glare issues (p=0.00). This result suggests that despite increasing light levels, the design of the lighting setup successfully mitigated the sensation of glare, contributing to greater comfort and satisfaction with the lighting environment (Table 4.10).

Table 4.10. ANOVA results across illuminance groups

variable	illuminance group	mean	p-value	variable	illuminance group	mean	p-value
CS	1.00	0.17	0.00***	comfort	1.00	12.26	0.00***
	2.00	0.33			2.00	14.55	
	3.00	0.45			3.00	15.81	
EML	1.00	111.82	0.00***	naturalness	1.00	12.64	0.00***
	2.00	328.14			2.00	14.00	
	3.00	673.52			3.00	14.74	
KSS1	1.00	3.85	0.00***	precision	1.00	26.92	0.00***
	2.00	3.50			2.00	30.51	
	3.00	3.10			3.00	31.57	
PA1	1.00	29.60	0.04**	satisfaction	1.00	14.47	0.00***
	2.00	29.81			2.00	18.95	
	3.00	31.94			3.00	21.55	
NA1	1.00	13.20	0.00***	GSV	1.00	1.52	0.00***
	2.00	12.10			2.00	1.36	
	3.00	11.37			3.00	1.24	
Landolt	1.00	37.38	0.00***	KSS2	1.00	4.00	0.00***
	2.00	29.08			2.00	3.38	
	3.00	34.45			3.00	3.06	
Stroop	1.00	977.16	0.00***	PA2	1.00	27.79	0.00***
	2.00	900.74			2.00	29.95	
	3.00	899.17			3.00	31.69	
N-back	1.00	72.73	0.53	NA2	1.00	12.32	0.00***
	2.00	73.42			2.00	11.58	
	3.00	75.44			3.00	11.08	

Statistical significance levels: ***when p-value<0.01, **when 0.01< p-value < 0.05, *when 0.05 < p-value < 0.1

The ANOVA analysis conducted examines the effects of daylight and LED color temperature settings on various performance and subjective metrics, categorized into four distinct groups: 1- daylight, 2- LED above 5000K, 3- LED between 4000K-5000K, and 4- LED below 4000K. The design of this analysis was aimed to identify how different lighting scenarios, particularly the spectral properties of LED lighting compared to natural daylight, influence circadian stimulus, visual performance, mood, and subjective experiences.

The results reveal significant variations across the groups for most metrics (Table 4.11). For Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML), Group 2 (LED above 5000K) shows the highest mean values (CS=0.35, EML=367.12), indicating that higher color temperatures are more effective at enhancing circadian activation, with p-values strongly supporting these findings (p=0.000). Conversely, Group 4 (LED below 4000K) shows the lowest effectiveness in circadian and melanopic lux levels.

Table 4.11. ANOVA results across LED color temperature groups

variable	LED CT group	mean	p-value
CS	1.00	0.26	0.00***
	2.00	0.35	
	3.00	0.32	
	4.00	0.23	
EML	1.00	286.41	0.00***
	2.00	367.12	
	3.00	332.29	
	4.00	208.11	
KSS1	1.00	3.87	0.00***
	2.00	3.64	
	3.00	3.09	
	4.00	3.60	
PA1	1.00	29.74	0.95
	2.00	30.02	
	3.00	30.28	
	4.00	30.00	
NA1	1.00	12.97	0.01**
	2.00	12.52	
	3.00	11.52	
	4.00	12.49	
landolt	1.00	39.43	0.00***
	2.00	29.72	
	3.00	27.83	
	4.00	33.10	
Stroop	1.00	1026.207	0.00***
	2.00	901.3486	
	3.00	878.9686	
	4.00	915.8577	
N-back	1.00	69.71519	0.02**
	2.00	74.28962	
	3.00	76.99174	
	4.00	73.26838	

variable	LED CT group	mean	p-value
comfort	1.00	11.34	0.00***
	2.00	14.64	
	3.00	15.53	
	4.00	13.93	
naturalness	1.00	12.32	0.00***
	2.00	12.97	
	3.00	14.20	
	4.00	14.41	
precision	1.00	25.92	0.00***
	2.00	30.21	
	3.00	31.13	
	4.00	29.71	
satisfaction	1.00	13.42	0.00***
	2.00	18.54	
	3.00	20.28	
	4.00	18.02	
GSV	1.00	1.59	0.00***
	2.00	1.42	
	3.00	1.20	
	4.00	1.39	
KSS2	1.00	4.09	0.00***
	2.00	3.48	
	3.00	2.92	
	4.00	3.65	
PA2	1.00	28.10759	0.13
	2.00	30.01639	
	3.00	30.10744	
	4.00	29.26838	
NA2	1.00	12.21519	0.06*
	2.00	11.86885	
	3.00	11.14876	
	4.00	11.81985	

Statistical significance levels: ***when p-value<0.01, **when 0.01< p-value < 0.05, *when 0.05 < p-value < 0.1

In terms of performance metrics such as the Landolt and Stroop tests, the results also suggest superior performance under higher color temperatures, with Groups 2 and 3 showing better visual acuity and faster cognitive response times, respectively. This trend is underscored by significant p-values (p=0.00 for both tests), confirming that the LED color temperature significantly impacts visual and cognitive task performance.

Subjective evaluations such as the Karolinska Sleepiness Scale (KSS), Positive Affect (PA), and Negative Affect (NA) show nuanced responses. While KSS scores improve significantly with higher color temperatures (Group 3 having the lowest mean at 3.09, p=0.00), the changes in PA and NA are less pronounced, with only marginal differences observed (PA p=0.949 and NA p=0.01), suggesting that emotional responses may be less sensitive to changes in color temperature. Comfort, naturalness, precision, and satisfaction all significantly improve with higher color temperatures, with Groups 2 and 3 generally experiencing the highest levels of subjective well-being. These findings are significant (p=0.00 for comfort, naturalness, precision, satisfaction), indicating that LED settings that mimic daylight conditions (closer to natural light) are perceived as more comfortable and satisfactory.

4.2.3. Multiple Regression Analysis

A large-scale multiple regression analysis was performed to determine the effects of physical environment and lighting conditions on office users' task performance, satisfaction, alertness, and mood. The dependent and independent variables used in the model are:

- Independent variables: room orientation, weather condition, experiment time and stage, glass type, indoor illuminance, colour temperature and dominant wavelength (indoor, outdoor, eye-level and workplane), LED dimmer and colour temperature settings, luminance ratios ($L_{workplane}/L_{screen}$, L_{wall}/L_{screen}, L_{window}/L_{screen}, $L_{window}/L_{workplane}$), CS and EML values, participant's age, gender, profession, eye disorder, visual eid, sleep duration, meal status, satisfaction with indoor temperature (Perc. T_{in}) and outdoor (Perc. T_{out}) weather conditions.
- Dependent variables: KSS, PANAS (PA, NA), Landolt test, Stroop score, N-back score, Glare Sensation Vote (GSV), survey questions regarding visual comfort (Q1-Q4), naturalness (Q5-Q8), precision (Q9-15) and satisfaction (Q16-Q20).

Prior to conducting the regression analysis, a preliminary step involved examining correlations among variables to ensure that multicollinearity did not bias the results. Correlation analysis was performed to identify any high correlations between variables, defined as a correlation coefficient (r) exceeding 0.8. This threshold was set to identify potential redundancy among predictors that could impact the validity of the regression model. When pairs of variables exhibited a correlation higher than 0.8, only one of the variables was included in the regression analysis to avoid multicollinearity, while the other was excluded. For instance, high correlations were found between outdoor and indoor illuminance, outdoor illuminance and outdoor SPD, eye-level illuminance and CCT with workplane illuminance and CCT, and eye-level illuminance with CS and EML. Multiple regression analysis was performed using R software. Multiple regression analysis results are given in Table 4.12, highlighted according to statistical significance levels (p-value < 0.05). Correlation coefficients were included to the table to determine the direction of the relationship between dependent and independent variables. Regarding the task performances and survey according to the results reported in Table 4.12,

- A statistically significant relationship was found between the error rates in the Landolt test and the stage of the experiment, glass type, indoor and workplane dominant wavelength, LED colour temperature setting and especially indoor colour temperature. In the second stage of the experiment, the error rate decreased. Performance decreases as the indoor colour temperature and dominant wavelength decrease. This indicates that the contrast on the paper increases towards white/cold light and the participants are able to distinguish details better. According to the positive correlation between the glass type and Landolt results, the higher transmittance of the glass provides better scores. The gender of the participant also had a significant impact on performance, with women being more successful.
- According to the results of the Stroop test performed on the computer, it can be said that there was a statistically significant decrease in the reaction time in the second stage of the experiment, that is, the participants were more successful at this stage. In addition, there is a high positive correlation between reaction time and age (reaction time increases with age).
- According to the N-back results, gender was highly influential in the correct matching rate – men are more successful. Another factor affecting performance was time; participants performed better in the afternoon. Although the statistical significance level is low, the correct matching rate decreased with the increase in eye-level illuminance.

On the other hand, it can be said that the mismatch rates increase as outdoor illuminance and colour temperature (cold light) increase.

- Regarding survey results, there is a significant difference between the experimental stages for almost all questions. Positive feedback increased in the second stage of the experiment. Eye-level illuminance has a negative effect on visual comfort. As the illuminance increased, visual comfort decreased. Even though the degree of significance is low, the negative correlation with the glass type indicates that as the transmittance value of the glass increases, the positive feedback regarding visual comfort increases.
- The effect of the glass type become prominent in the answers regarding naturalness in the questionnaire. Users reported that as the transmittance value of the glass decreases, the light and objects in the room appear more artificial. Increasing the LED colour temperature had a similar effect.
- Eye-level illuminance and LED dimmer setting positively affect the answers related to precision in the questionnaire. It has been reported that the texture and details of the objects appear more clearly with the increase in the illuminance.
- Glass type and the LED dimmer setting are effective in the answers regarding general lighting quality and satisfaction. The positive feedback decreased with the decrease of the transmittance of the glass and increased with the increase of the LED light intensity.
- Regarding visual discomfort assessment (GSV), the discomfort decreased as the transmittance of the glass increased. The sensation of discomfort decreased in the second stage of the experiment.
- Considering KSS results at the beginning and the end of the experiment (KSS1, KSS2), the participant's alertness changed according to the sleep duration and the stage of the experiment. However, according to the answers given at the end of the experiment, LED dimmer and colour temperature settings also have a statistically significant effect. The LED setting indicates that brighter and colder light increases alertness.
- Time, indoor temperature and outdoor weather conditions were more effective than lighting conditions in the PANAS results. Positive mood increased in the afternoon.

Circadian indicators (CS and EML) could not be considered in the same regression model, as they were highly correlated with eye-level illuminance. These variables were evaluated by establishing two separate regression models.

Table 4.12. Results of multiple regression analysis

	KSS1	Landolt	Stroop	Nback	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	GSV	KSS2	PA	NA
Orientation	-100.60	-4447.00	-43430.00	985.00	181.20	-98.00	15.93	102.80	-270.30	117.50	196.30	-759.30	-64.95	-83.85	-27.77	-78.49	77.14	99.83	228.30	-53.21	-153.50	-151.60	-119.40	-202.30	94.61	551.40	-954.90	34.30
Stage	-760.10	-5712.00	-140600.00	3194.00	189.40	794.10	562.50	1174.00	874.20	763.90	104.20	158.90	274.70	198.50	572.30	354.10	387.00	394.40	75.12	815.40	1158.00	1033.00	1040.00	813.40	-288.90	-689.80	1392.00	-1175.00
Time	-58.77	-225.70	18.19	1361.00	-18.26	-0.89	5.56	6.22	25.51	-19.19	13.29	18.28	-22.52	-28.13	-12.29	-4.88	9.73	10.14	36.50	28.77	14.51	34.26	27.27	11.54	20.58	-67.53	521.90	47.86
Glass type	28.69	1038.00	3793.00	-527.60	35.91	-55.55	-75.81	-23.27	-91.45	-32.19	-82.43	-64.18	-50.35	-22.03	-28.66	-13.48	-22.53	-44.51	-32.48	-13.99	-42.21	-91.73	-49.58	-63.35	33.54	59.63	-22.78	-1.72
T_{in}	-46.57	1128.00	-1969.00	-205.30	32.83	-11.09	-10.33	21.23	-31.49	3.27	31.15	-26.64	-21.55	0.39	4.30	-17.93	-4.21	5.62	-7.14	-22.07	-11.78	-37.42	-25.16	-18.98	7.91	-39.09	-133.90	-43.06
T_{out}	27.48	-305.40	-1636.00	241.50	-8.19	-2.30	-6.42	-10.12	2.69	-13.57	-25.06	-8.80	6.41	-1.33	-15.64	1.56	-15.38	-17.19	-18.53	-16.65	-26.29	-3.25	4.11	-12.69	-2.31	46.23	-190.40	19.65
Weather	-23.70	1333.00	-4812.00	-864.60	-26.52	-141.30	-54.65	-6.56	11.25	28.92	-56.50	-2.88	-36.78	0.71	6.37	63.69	39.97	10.02	31.88	46.38	-45.78	-15.90	23.01	-43.66	-49.86	-117.20	999.70	-166.90
Outdoor Illum.	0.01	-0.05	-0.07	0.04	0.00	0.00	-0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	-0.02	0.00
Outdoor CCT	-0.01	-0.17	1.30	0.25	0.00	-0.04	-0.03	0.03	-0.02	-0.01	-0.02	0.01	-0.01	-0.01	-0.01	0.02	0.00	-0.01	-0.01	0.02	0.02	-0.01	0.00	0.00	0.00	-0.02	0.11	0.09
Indoor CCT	0.00	-0.23	-0.01	-0.06	0.00	0.00	0.00	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00	-0.01	0.00	0.00	0.00	0.01	0.00	0.00
Indoor SPD	-0.42	-78.37	-242.80	29.65	-1.33	-1.67	0.15	0.75	-2.72	3.03	-15.65	-2.04	2.01	0.53	1.43	-1.22	1.76	1.08	-10.86	-0.46	0.34	-3.74	-1.29	-0.82	0.23	6.01	-12.02	2.02
LED Dimmer	-4.09	62.75	19.28	31.89	11.75	4.44	5.63	8.15	-1.85	6.30	0.50	-3.34	2.19	3.22	4.35	5.74	5.73	6.61	-0.34	11.56	6.73	4.10	5.92	8.82	-2.19	-7.61	35.83	-0.74
LED CT	-0.04	-3.87	-8.52	0.31	0.14	-0.12	0.02	-0.06	-0.25	0.08	0.08	-0.61	-0.04	0.00	0.05	0.06	0.04	0.06	-0.15	-0.06	-0.18	-0.05	0.07	-0.01	-0.01	-0.22	0.29	0.00
$L_{workplane}/L_{screen}$	-19.80	-30.71	-207.80	172.90	7.46	-2.02	-2.54	8.29	8.46	12.57	3.69	-2.34	1.13	7.56	9.53	5.48	7.53	7.88	4.59	2.03	9.60	8.26	3.63	9.68	2.28	-13.68	47.82	-0.63
L_{wall}/L_{screen}	1.96	-47.38	-47.71	7.26	0.73	-1.31	-0.60	-0.17	2.29	0.42	-0.34	0.07	0.00	0.15	-0.73	0.27	0.40	0.16	0.73	-1.31	-0.40	-1.77	-2.54	-0.59	0.51	0.63	-14.93	-1.23
L_{window}/L_{screen}	2.09	11.82	196.80	-4.45	0.32	0.08	0.74	0.30	-0.16	-0.47	0.41	-0.17	1.17	0.62	0.94	1.06	0.88	0.48	1.07	0.39	0.31	-0.08	0.81	0.81	0.72	3.43	-8.08	0.20
$L_{window}/L_{workplane}$	-8.96	-2.23	-926.00	33.81	0.12	-0.82	-6.43	-2.88	4.24	1.08	-1.94	0.18	-3.67	-1.69	-0.91	-2.20	-1.94	-2.78	-6.55	-2.30	-2.64	0.71	-2.28	-4.77	-2.39	-14.25	24.87	3.46
Eye-level Illum.	-0.05	-0.51	-30.08	-8.00	0.21	-0.70	-0.86	-0.57	-0.01	-0.48	0.03	0.28	-0.74	-0.67	-0.70	-0.49	-0.45	-0.33	0.06	-0.18	-0.44	-0.33	-0.32	-0.68	0.26	0.16	-0.40	0.53
Eye-level CCT	-0.01	0.02	0.08	0.00	-0.02	0.01	0.02	-0.01	-0.02	-0.03	-0.01	-0.02	-0.01	0.00	0.02	0.00	-0.03	-0.02	0.00	-0.02	-0.01	-0.01	0.00	0.00	0.00	0.01	-0.05	0.04
Eye-level SPD	13.78	-29.41	936.20	-182.60	-2.20	0.83	-0.78	-2.89	3.72	-2.79	-4.37	-1.07	-1.47	2.27	3.82	-2.66	-1.65	-2.86	-3.12	-6.37	-5.19	-5.00	-8.04	-5.68	-1.39	10.62	28.31	-3.40
Workplane SPD	-10.15	-182.60	-1215.00	99.57	5.45	-4.01	-0.39	-4.05	-9.41	2.01	2.99	-1.12	-1.33	-3.96	-4.11	1.63	-0.88	2.02	-1.88	6.23	-0.70	-1.78	6.11	0.34	0.11	-13.02	-14.48	3.37
Age	-16.45	244.70	5843.00	125.50	-1.88	0.26	-1.37	13.04	13.35	-5.14	-5.12	18.55	6.44	-8.03	-6.66	-10.53	-1.49	-2.67	-10.36	14.71	7.41	20.63	0.48	1.56	-9.04	-24.88	220.40	1.75
Gender	419.20	-3731.00	12030.00	-7509.00	-2.81	-82.37	50.21	99.89	-27.86	109.20	-34.48	-104.90	16.88	-2.68	165.80	109.50	122.30	45.54	34.86	180.60	32.57	173.20	73.48	-2.28	-78.43	275.10	-2986.00	-666.40
Perc. T_{in}	-161.80	-2494.00	-17570.00	-1234.00	-14.54	222.30	213.50	-0.49	-5.16	91.09	129.30	25.44	117.10	63.44	92.71	126.40	68.13	64.64	126.30	-24.39	84.73	172.50	175.70	133.90	-68.99	-123.30	1254.00	-229.10
Perc. T_{out}	-164.80	2189.00	14150.00	-765.90	11.32	52.77	-6.55	49.39	87.33	74.70	72.28	22.52	52.76	55.47	66.17	27.08	103.50	119.40	55.00	94.48	89.72	49.74	71.69	77.63	-12.84	-192.40	534.10	-204.90
Visual Eid	161.10	887.10	4677.00	375.70	-52.88	-10.31	-58.15	-65.19	-43.99	-59.35	-48.45	80.95	-117.30	-124.50	-118.30	-129.10	-61.17	-66.04	-47.18	-32.21	11.61	-53.25	-111.10	-42.03	-15.37	191.80	-108.10	-191.90
Eye Disorder	37.87	-66.21	6676.00	-673.90	9.45	5.77	19.35	14.21	39.63	-13.26	39.25	19.35	-23.84	-19.05	8.61	-14.31	2.55	-5.38	44.44	29.20	-0.68	10.67	-9.05	3.33	13.36	57.77	24.53	228.40
Sleep Duration	-196.50	-217.00	5995.00	-151.30	12.60	10.83	-10.59	-18.87	-50.54	-30.30	-17.02	19.54	-2.67	-4.59	-23.19	-25.24	-14.72	-29.00	-18.02	-7.08	-16.11	-10.58	-14.00	-9.27	11.20	-168.30	97.61	-63.68
Meal Staus	-40.07	-478.80	5183.00	-295.90	-1.72	-54.27	-29.50	-19.96	33.49	-30.07	19.07	-25.23	-3.29	-24.20	-60.45	-36.51	9.44	-71.68	-16.63	-47.73	-42.01	-33.19	-73.90	-32.14	13.70	-30.34	-233.00	-3.04

Statistical significance level:	p-value < 0.001	'***'	0.001 < p-value < 0.01	'**'	0.01 < p-value < 0.05	'*'	0.05 < p-value < 0.1	'.'

Multiple regression models also enabled to find the weight values of the lighting parameters that affect the performance indicators. Using coefficients in the table, expected Landolt score can be formulated as below:

Error Rate = 196200 – 4447.00*orientation – 5712.00*stage – 225.70*time + 1038.00*glass +1128.00*weather – 305.40*EH1 + 1333.00*CCT1 – 0.23*CCT2 – 78.37*SPD2 + 62.75*Dimmer – 3.87*CT – 30.71*Lum1 – 47.38*Lum2 + 11.82*Lum3 – 2.23*Lum5 – 0.51*EV3 + 0.02*CCT3 – 29.41*SPD3 – 182.60*SPDw + 244.70*age – 3731.00*gender – 2494.00*indoor + 2189.00*outdoor + 887.10*visualeid - 66.21*disorder – 217.00*sleep – 478.80*meal

Similarly, a formula can be written and weight values can be found for Stroop, n-back, sleepiness, mood, GSV and survey results. However, R^2 was found as 0.15, meaning that only 15% of the variation in the error rate can be explained by the physical and lighting parameters in the model.

4.3. Artificial Intelligence Models

4.3.1. Artificial Neural Networks

Artificial Neural Networks (ANN) and fuzzy logic models were prepared by determining the most appropriate and most effective parameters for artificial intelligence models. The collected data (measured objective data) were used to establish and test the artificial intelligence model (ANN), and the participants' task performances and subjective evaluations were estimated. The most significant and effective variables in the regression analysis were taken into account in determining the ANN input parameters. Participants’ work performance (Landolt, Stroop, N-back), mood and alertness (KSS and PANAS), and satisfaction (visual comfort, naturalness, precision, light quality, and GSV) were predicted by establishing separate models. The current version of Lumivero/Neuraltools software was used to set up the prediction models. 80% of the data set was used for training, whereas 20% was used for prediction (testing). The input parameters of the ANN model can be summarized as in Table 4.13. Lumivero offers two different algorithms for neural network training: Multi-Layer Feed Forward Networks (MLF) and Probabilistic Neural Nets (PN)/Generalized Regression

Neural Nets (GRN). After several trials, the PN/GRN algorithm was used to achieve better predictions. Simulation settings are shown in Figure 4.17.

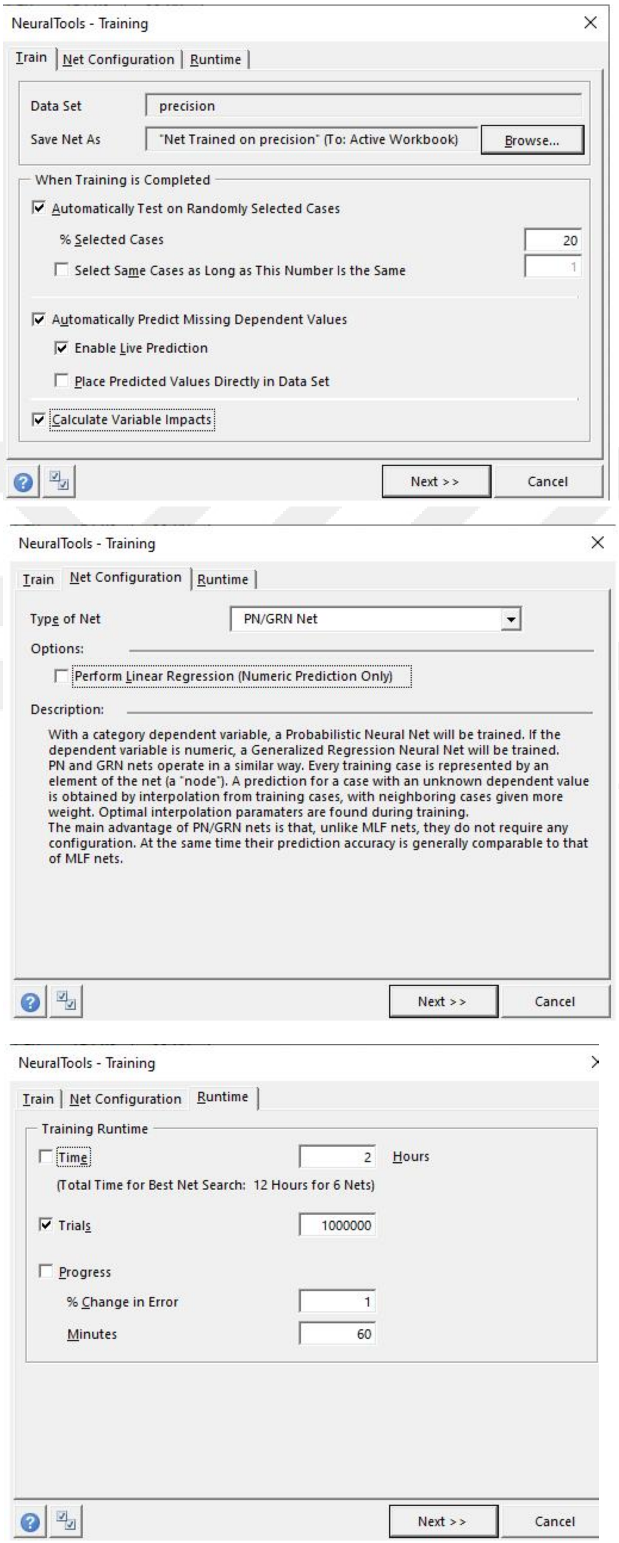


Figure 4.17. Lumivero/Neuraltools simulation settings

Table 4.13. Value ranges of inputs in the ANN model

Input	**Range**	
	Min	**Max**
Stage (of the experiment)	1	2
Glass type	1	10
EH1 (Outdoor Illuminance)	90 lux	94.000 lux
EH2 (Indoor Illuminance)	22 lux	62.000 lux
CCT2 (Indoor Correlated Color Temperature)	1.900 K	100.000 K
SPD2 (Indoor Dominant Wavelenght)	477 nm	590 nm
Lum4 (Luminance at wall/workplane)	0.08	113.82
Lum5 (Luminance at window/workplane)	0.11	202.68
CCT3 (Eye-level Correlated Color Temperature)	1.800 K	100.000 K
SPD3 (Eye-level Dominant Wavelenght)	482 nm	590 nm
EML (Equivalent Melanopic Lux)	13 lux	1.785 lux

In the analysis of the Landolt test, which serves as a measure of participants' work performance and visual acuity, the predictive modeling demonstrated a capability to accurately forecast error rates. During the training phase, the model predicted error rates with an accuracy of 49.2%, and during the testing phase, the accuracy was 42.3%, as detailed in Table 4.14. Notably, the glass type emerged as the most influential parameter in predicting these error rates. Furthermore, the coefficient of determination (R^2) between the predicted and actual test results during the training phase was recorded at 0.32, indicating a moderate level of predictability (Figure 4.18).

Table 4.14. Landolt training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	103	-
% Bad Predictions (30% Tolerance)	50.79%	56.73%
Root Mean Square Error	15.36	17.02
Mean Absolute Error	12.09	13.60
Std. Deviation of Abs. Error	9.46	10.24

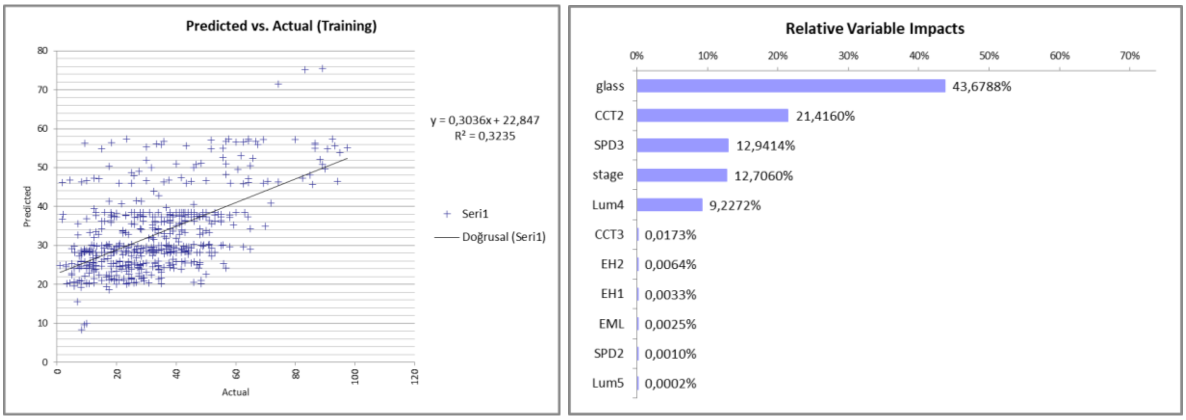


Figure 4.18. Predicted versus measured error rate in the Landolt test (left) and influence of input parameters in the developed ANN model (right)

The predictive analysis of reaction times in the Stroop test demonstrates a high degree of accuracy, with the model achieving a predictive success rate of 90.4% during the training phase and an even higher rate of 93.6% during the testing phase (Table 4.15). The stage of the experiment was identified as the most significant parameter influencing the prediction accuracy, underscoring the impact of lighitng conditions on cognitive processing speeds. Additionally, R^2 between the predicted and actual test results in the training phase was calculated at 0.24 (Figure 4.19).

Table 4.15. Stroop training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	81	-
% Bad Predictions (30% Tolerance)	9.59%	6.38%
Root Mean Square Error	157.59	175.55
Mean Absolute Error	125.70	133.40
Std. Deviation of Abs. Error	95.05	114.12

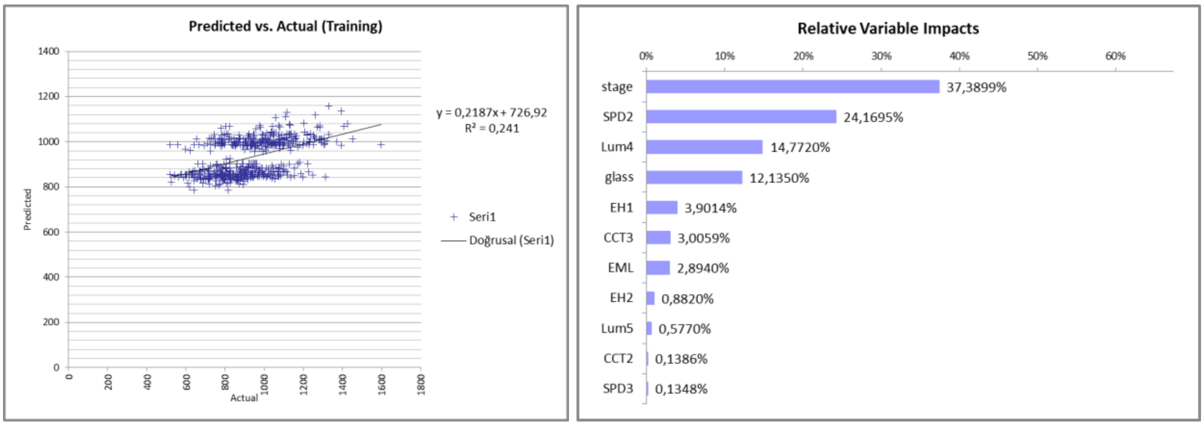


Figure 4.19. Predicted versus measured reaction time in the Stroop test (left) and influence of input parameters in the developed ANN model (right)

The accuracy of predictions for the correct matches rate in the N-back test was notably high, with 82.6% in the training phase and 85.1% in the testing phase (Table 4.16). The indoor dominant wavelength emerged as the most influential parameter in these predictions. R^2 for the predicted versus actual results during the training phase was low at 0.02, suggesting that while the model is generally effective, it captures only a small fraction of the variability in the data (Figure 4.20).

Table 4.16. N-back training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	84	-
% Bad Predictions (30% Tolerance)	17.40%	14.89%
Root Mean Square Error	19,20	16.79
Mean Absolute Error	14.89	13.70
Std. Deviation of Abs. Error	12.12	9.70

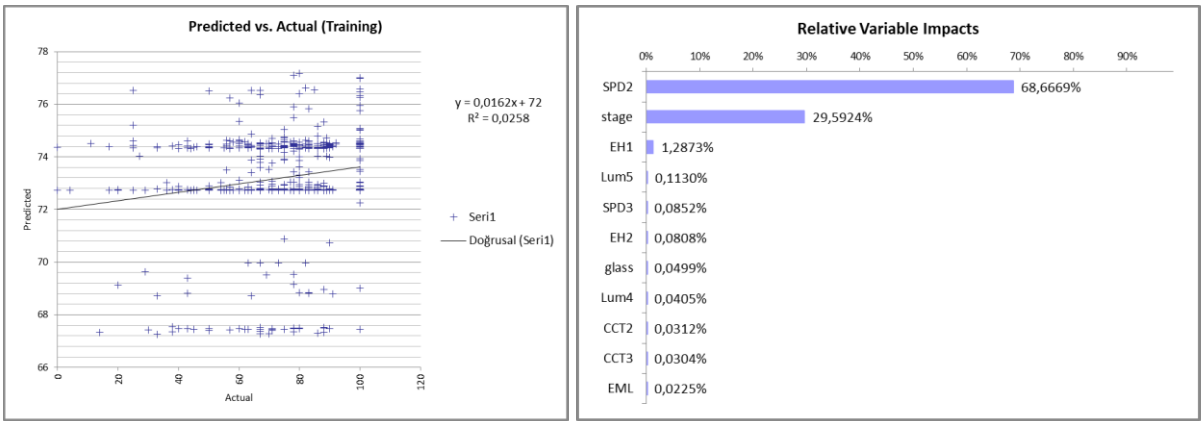


Figure 4.20. Predicted versus measured correct match rate in the N-back test (left) and influence of input parameters in the developed ANN model (right)

The KSS scores, which indicate users' alertness or sleep state, were predicted with an accuracy of 49.7% during the training phase and 44.7% during the testing phase (Table 4.17). The dominant wavelength at eye-level was identified as the most critical predictive factor, with luminance ratios also playing a significant role. The R^2 value of 0.20 indicates a modest fit, showing that the model reasonably reflects the influence of lighting conditions on alertness (Figure 4.21).

Table 4.17. KSS training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	142	-
% Bad Predictions (30% Tolerance)	50.26%	55.31%
Root Mean Square Error	1.578	1.75
Mean Absolute Error	1.24	1.36
Std. Deviation of Abs. Error	0.96	1.10

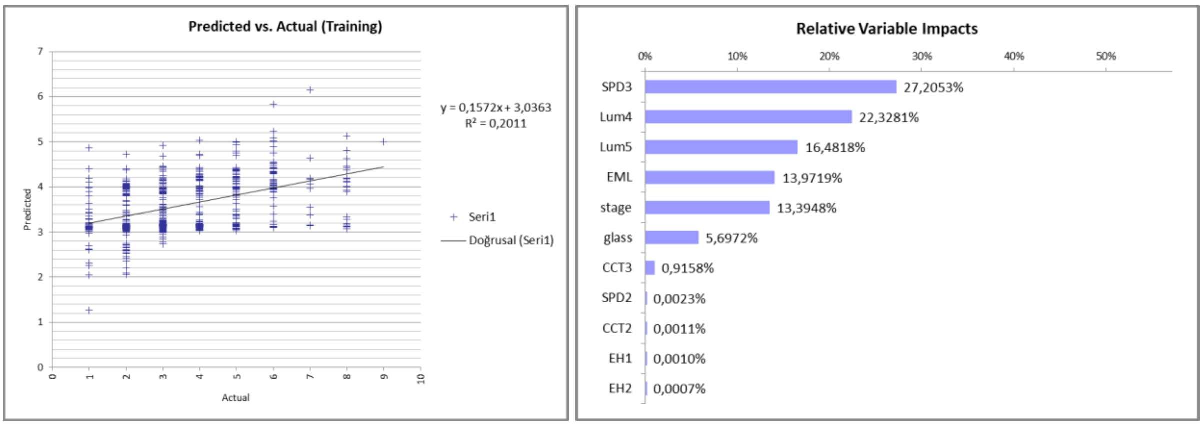


Figure 4.21. Predicted versus measured KSS score (left) and influence of input parameters in the developed ANN model (right)

For the PANAS scores, which assess mood and emotional states, the predictions were reasonably accurate at 74.1% during the training phase and 69.5% in the testing phase (Table 4.18). The most impactful parameter was the luminance ratio between the wall and workplane, with outdoor illuminance also significantly affecting the predictions. An R^2 of 0.20 suggests that the model effectively captures the impact of these environmental factors on mood variations (Figure 4.22).

Table 4.18. PANAS training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	120	-
% Bad Predictions (30% Tolerance)	25.93%	30.49%
Root Mean Square Error	7.45	8,66
Mean Absolute Error	6.10	7.28
Std. Deviation of Abs. Error	4.27	4.69

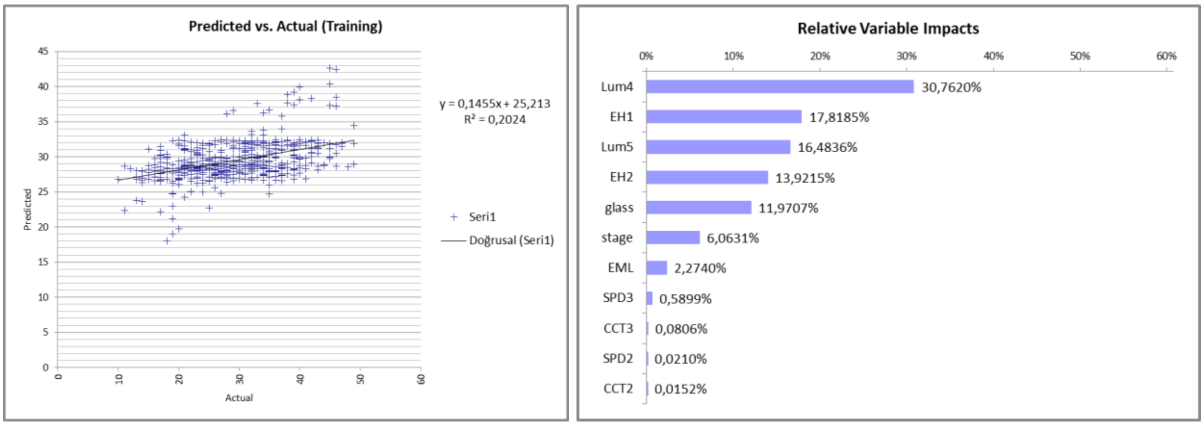


Figure 4.22. Predicted versus measured PANAS score (left) and influence of input parameters in the developed ANN model (right)

Predictions for GSV, reflecting participants' perceived glare, achieved accuracy rates of 44.6% in the training phase and 39% in the testing phase (Table 4.19). The experimental stage was the most significant predictor, followed by glass type. The R^2 value of 0.10 indicates a lower predictability, highlighting challenges in modeling subjective glare sensations based on environmental and experimental variables (Figure 4.23).

Table 4.19. GSV training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	111	-
% Bad Predictions (30% Tolerance)	55.41%	60.99%
Root Mean Square Error	0.59	0.60
Mean Absolute Error	0.48	0.50
Std. Deviation of Abs. Error	0.34	0.33

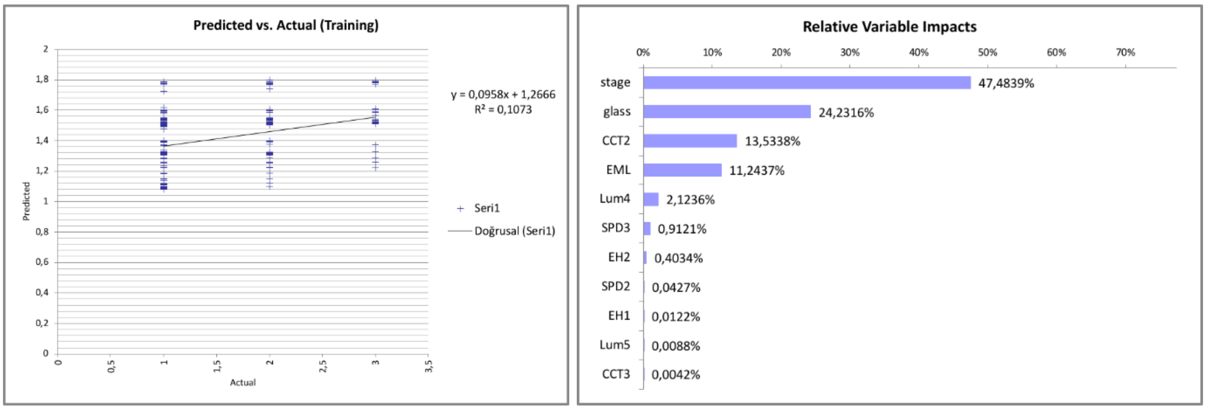


Figure 4.23. Predicted versus measured GSV score (left) and influence of input parameters in the developed ANN model (right)

The prediction model for comfort scores demonstrated high accuracy, achieving a prediction rate of 88.6% in both the training and testing phases (Table 4.20). The stage of the experiment was identified as the most significant predictor, reflecting how dynamic LED lighting can impact perceived comfort. A relatively high R^2 value of 0.41 indicates a strong correlation between predicted and actual test results, suggesting that the model is robust in capturing the factors influencing comfort (Figure 4.24).

Table 4.20. Comfort training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	77	-
% Bad Predictions (30% Tolerance)	11.36%	11.34%
Root Mean Square Error	2.31	2.47
Mean Absolute Error	1.85	2.05
Std. Deviation of Abs. Error	1.39	1.38

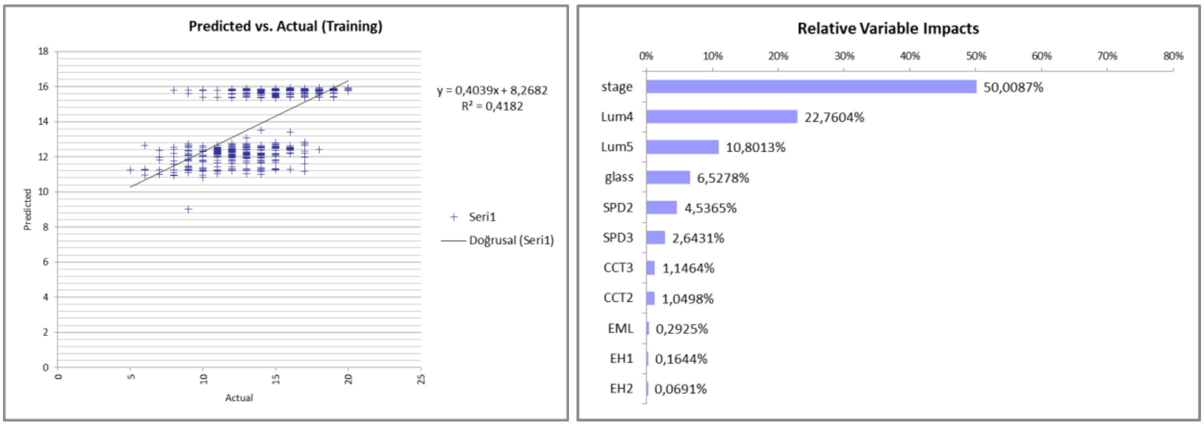


Figure 4.24. Predicted versus measured comfort score (left) and influence of input parameters in the developed ANN model (right)

Naturalness scores were predicted with high accuracy, reaching 89.7% in the training phase and 86.5% in the testing phase (Table 4.21). The indoor correlated color temperature (CCT2) was the most significant predictor, with Equivalent Melanopic Lux (EML) also playing a crucial role in the model. The R^2 value of 0.48 in the training phase signifies a strong predictive capacity, indicating that the model effectively captures how indoor lighting characteristics influence perceptions of naturalness (Figure 4.25).

Table 4.21. Naturalness training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	89	
% Bad Predictions (30% Tolerance)	10.30%	13.47%
Root Mean Square Error	2.26	2.40
Mean Absolute Error	1.76	1.92
Std. Deviation of Abs. Error	1.42	1.43

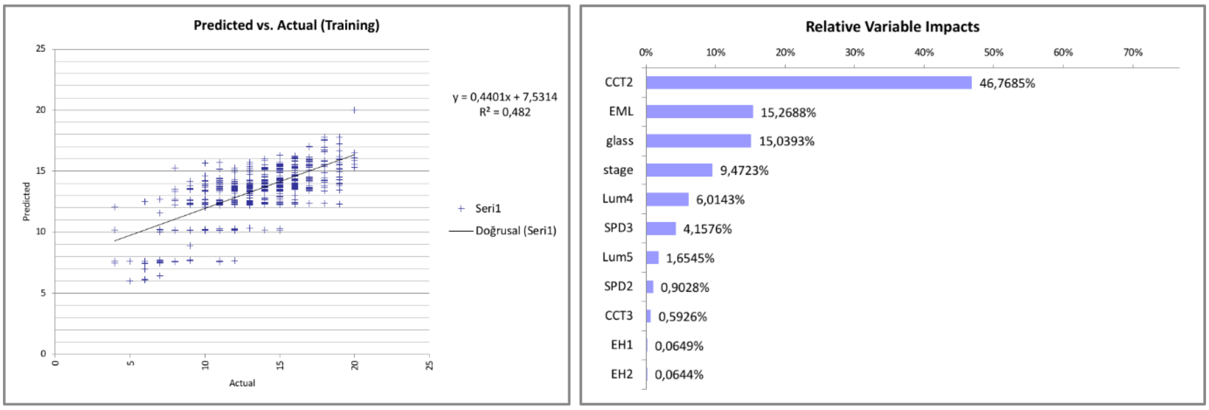


Figure 4.25. Predicted versus measured naturalness score (left) and influence of input parameters in the developed ANN model (right)

Precision scores in the survey can be well predicted at a rate of 94.3% in the training phase and 90.8% in the testing phase (Table 4.22). The most effective parameter in the prediction was glass type. The R^2 of the predicted and actual test results during the training phase was found to be 0.36 (Figure 4.26).

Table 4.22. Precision training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	97	
% Bad Predictions (30% Tolerance)	5.68%	9.21%
Root Mean Square Error	3.91	4.43
Mean Absolute Error	2.99	3.52
Std. Deviation of Abs. Error	2.52	2.67

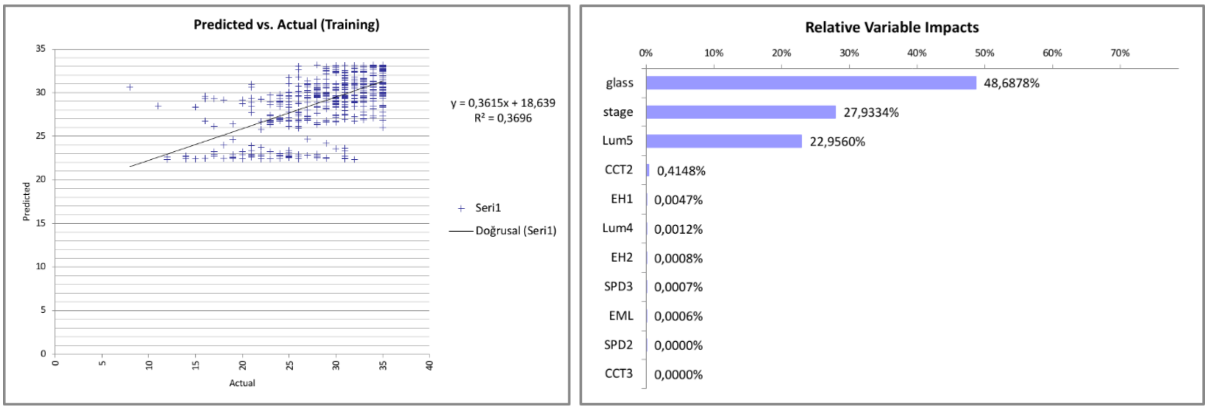


Figure 4.26. Predicted versus measured precision score (left) and influence of input parameters in the developed ANN model (right).

Satisfaction scores in the survey can be well predicted at a rate of 84.2% in the training phase and 75.2% in the testing phase (Table 4.23). The most effective parameter in the prediction was luminance ratio (wall/workplane). Equivalent Melanopic Lux (EML) was the second effective parameter. The R^2 of the predicted and actual test results during the training phase was found to be 0.54 (Figure 4.27).

Table 4.23. Satisfaction training and testing report

	Training	**Testing**
Number of Cases	563	141
Number of Trials	96	-
% Bad Predictions (30% Tolerance)	15.80%	24.82%
Root Mean Square Error	3.42	3.97
Mean Absolute Error	2.67	3.11
Std. Deviation of Abs. Error	2.13	2.46

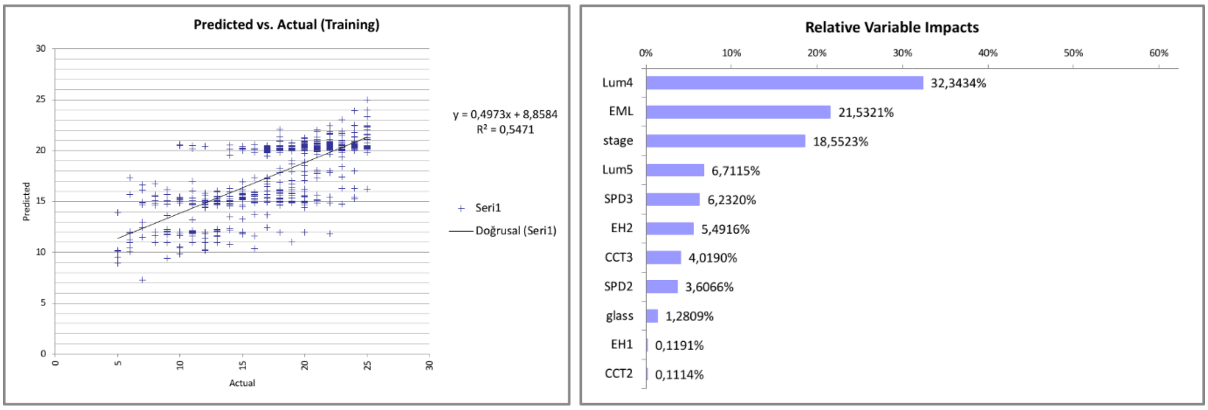


Figure 4.27. Predicted versus measured satisfaction score (left) and influence of input parameters in the developed ANN model (right)

4.3.2. Fuzzy Logic

In this section, a detailed exploration of Fuzzy Logic models is presented, providing a sophisticated framework for analyzing complex data where traditional binary distinctions (true/false, yes/no) fall short. Fuzzy Logic, a form of multi-valued logic derived from fuzzy set theory, deals with reasoning that is approximate rather than fixed and exact. Unlike binary logic, where variables are either 0 or 1, Fuzzy Logic variables have a range of possibilities, making it exceptionally suitable for capturing the uncertainty and subjective variability in human perceptual and performance data. Fuzzy Logic is often employed in systems where input data are inherently uncertain and precise modeling is challenging. It is particularly valuable in decision-making systems that mimic human reasoning, as it accommodates imprecision in classifications, such as distinguishing levels of comfort or satisfaction. The ability of Fuzzy Logic to handle degrees of truth rather than absolutes allows it to manage the ambiguity and continuous variability found in real-world scenarios, making it a powerful tool for behavioral sciences, engineering, and more.

In this study, Fuzzy Logic was applied to analyze the data collected from various performance metrics and lighting measurements. All data, including performance results and lighting measurements, were initially classified into low, medium, and high groups based on their distribution observed in scatterplots. This classification took into consideration the findings from statistical analyses and artificial intelligence models implemented in earlier stages of the research. Influential variables identified as having a significant impact on performance indicators were selected as inputs for the fuzzy logic model. For each input and performance indicator, the values were arranged from minimum to maximum, and breakpoints were strategically placed to divide the dataset evenly into three fuzzy sets: low, medium, and high. This segmentation facilitated a nuanced analysis of how different levels of input variables influenced performance outcomes across a spectrum of conditions. The Fuzzy Logic models were constructed and refined using Matlab FIS toolbox, which provided a robust platform for simulating complex interactive systems and adjusting model parameters to enhance accuracy and reliability. This approach allowed for a dynamic interpretation of the data, reflecting the subtle gradations and complexities inherent in human-lighting interactions.

Figure 4.28 presents Fuzzy Logic model design for predicting Landolt score based on glass type, indoor CCT, and CS value. In the Landolt test, the error rate below 30% represents optimal performance, demonstrating the highest level of visual precision and cognitive processing by the participants. This threshold was established based on the performance data and is indicative of superior visual acuity under specific environmental conditions. The best performance in the Landolt test, as characterized by this low error rate, is typically observed under the following conditions:

- Glass type: G1 (clear glass), G2 (smart glass) or G4 (solar low-e)
- Circadian Stimulus (CS): in the range of 0.15 – 0.30 or 0.30 – 0.40
- Indoor Color Temperature (CCT2): in the range of 0-5500K

Table 4.24. Example of rules regarding the best Landolt score

Input variables			**Output**
Glass type	*CS*	*CCT2*	*Landolt (error rate)*
G1	0.35	3000K	20.4%
G2	0.20	4500K	19.7%
G4	0.30	5500K	18.7%

Table 4.24 demonstrates how varying combinations of glass type, circadian stimulus, and indoor color temperature can influence visual task performance in a controlled environment. Although each configuration of inputs results in varying error rates, all successfully keep these rates below the 30% threshold, indicating optimal performance.

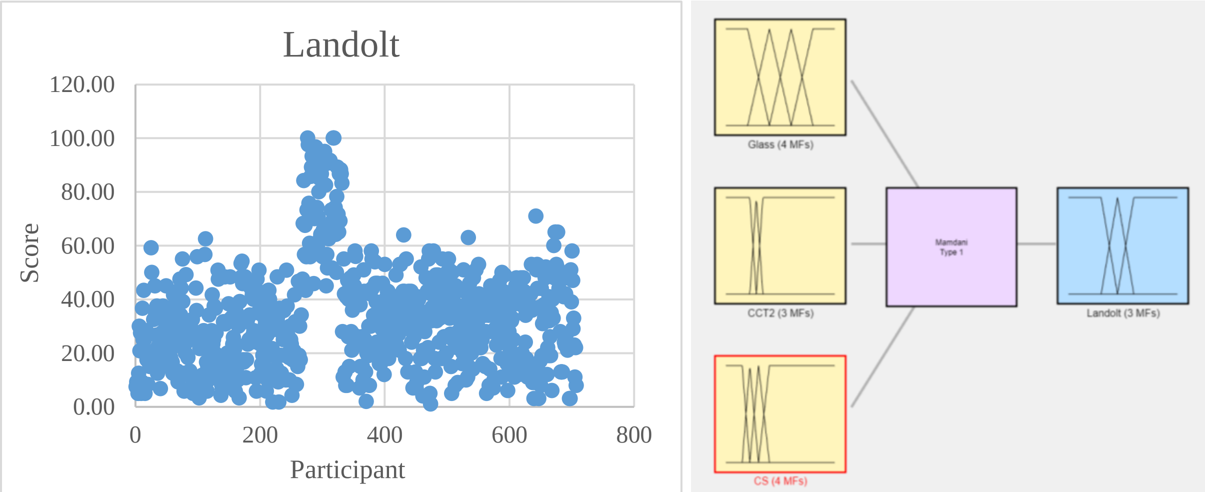


Figure 4.28. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for Landolt test

Figure 4.29 presents Fuzzy Logic model design for predicting Stroop score based on glass type, indoor CCT, and CS value. In the Stroop test, a response time of less than 800 ms indicates the best performance. Accordingly, the best Stroop score can be obtained for this category when the following conditions are met:

- Glass type: G2 (smart glass), G3 (low-e), G4 (solar low-e) or G5 (smoked solar low-e)
- Eye-Level Illuminance (EV3): in the range of 200 – 350 lux
- Indoor Color Temperature (CCT2): in the range of 5100K – 6700K

Table 4.25 presents combinations of glass type, eye-level illuminance, and indoor color temperature that are optimal for achieving the best scores in the Stroop test.

Table 4.25. Example of rules regarding the best Stroop score

Input variables			**Output**
Glass type	*EV3*	*CCT2*	*Stroop (reaction time)*
G2	250 lux	6500K	439 ms
G3	340 lux	5200K	635 ms
G5	300 lux	6000K	462 ms

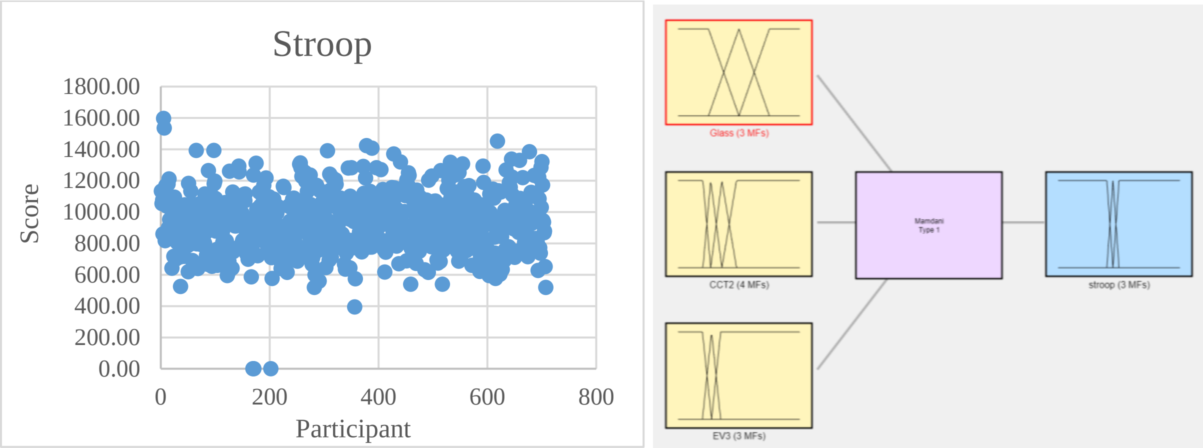


Figure 4.29. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for Stroop test

Figure 4.30 shows distribution of N-back scores and membership functions of input and output in the Matlab Fuzzy Model. In the N-back test, the best performance indicator is if the correct match rate is below 60%. The impact of lighting measurements on N-back scores was found to be minimal, therefore only one condition was established for this parameter.

- Equivalent Melanopic Lux (EML): 300 lux and above

Table 4.26 illustrates the variation in N-back test scores associated with Equivalent EML values below and above 300 lux.

Table 4.26. Example of rules regarding the best N-back score

Input variables	**Output**
EML	*N-back (correct matches)*
150 lux	79%
300 lux	32.3%
1000 lux	32.3%

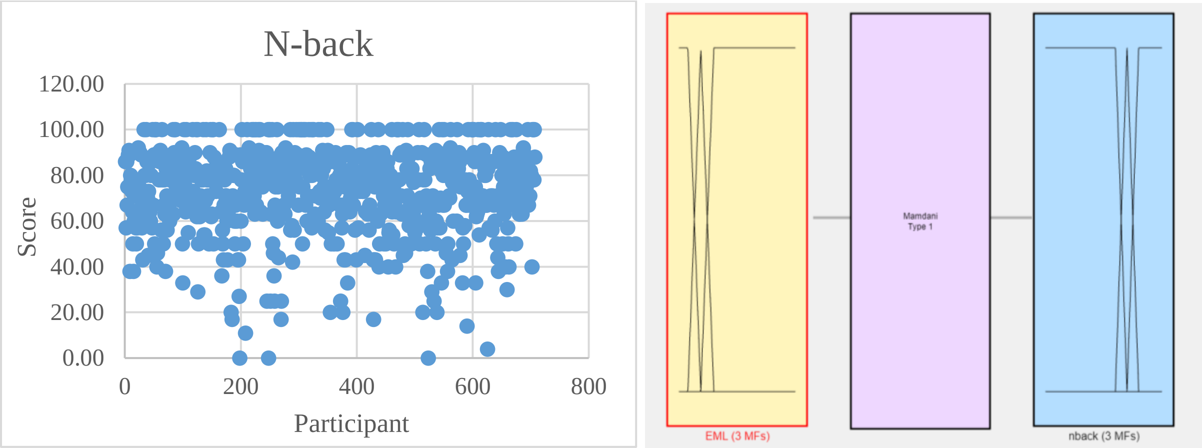


Figure 4.30. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for N-back test

In the assessment of alertness using the Karolinska Sleepiness Scale (KSS), scores of "1, 2, and 3" indicate that an individual is "awake/attentive." Table 4.27 exemplifies the rules derived from the fuzzy logic model regarding the best KSS scores, showing the combinations of glass type, LED dimmer settings, and EML values that yield the most favorable outcomes in terms of alertness. Optimal alertness, as reflected by these low KSS scores, is most reliably achieved under specific conditions that have been empirically determined through the study. These conditions include:

- Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e) or G7 (bronze solar low-e)
- LED Dimmer setting: in the range of %45 – %100
- Equivalent Melanopic Lux (EML): Above 250 lux

Figure 4.31 illustrates a Mamdani-type fuzzy logic system that predicts the KSS2 output based on three inputs, each with three membership functions (low, medium, high).

Table 4.27. Example of rules regarding the best KSS score

Input variables			**Output**
Glass type	*Dimmer*	*EML*	*KSS*
G1	80%	250 lux	0.76
G3	50%	500 lux	0.80
G7	60%	750 lux	0.84

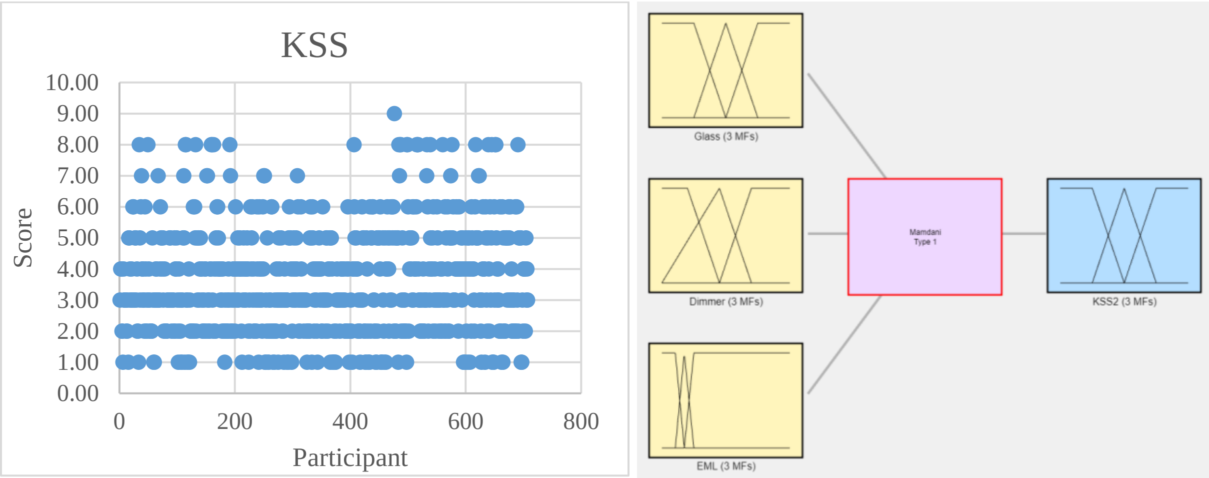


Figure 4.31. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for KSS

Figure 4.32 displays the fuzzy logic model's guidelines for obtaining the best scores on the PANAS test, which measures mood and emotional state. A score of 35 or higher signifies a positive emotional state. Optimal outcomes are achieved under specific conditions exemplified in Table 4.28, including glass types and LED dimmer setting. The best PANAS score can be obtained for this category when the following conditions are met:

- Glass type: G1 (clear glass) or G7 (bronze solar low-e)
- LED Dimmer setting: 70 and above

Table 4.28. Example of rules regarding the best PANAS score

Input variables		**Output**
Glass type	*Dimmer*	*PANAS*
G1	85%	41.30
G7	70%	41.30
G7	100%	41.30

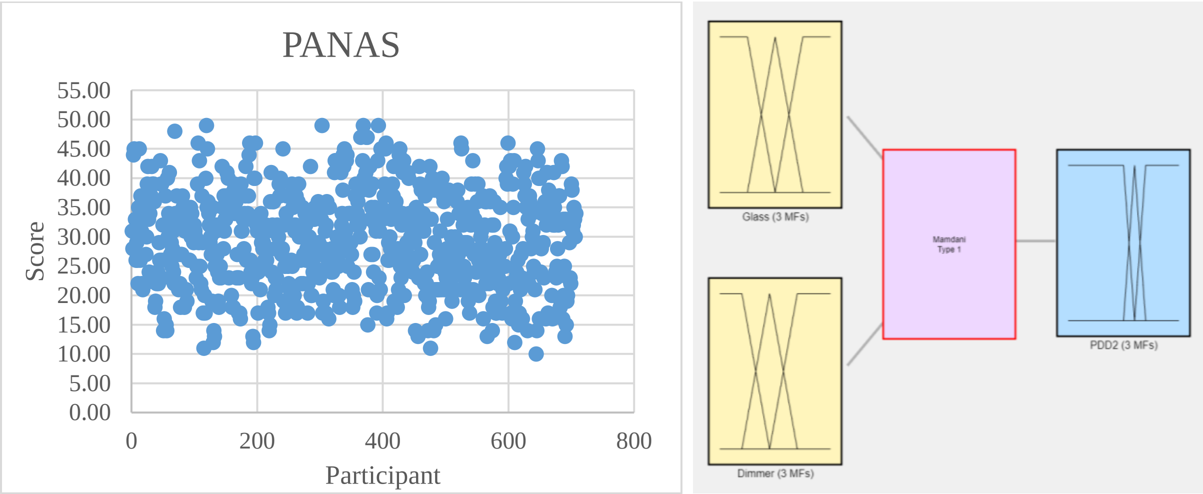


Figure 4.32. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for PANAS

In the Glare Sensation Vote (GSV) test used to assess visual discomfort, a response of '1-imperceptible' is indicative of the most favorable lighting conditions. Table 4.29 presents specific configurations of glass type, window/screen luminance ratio, and eye-level illuminance that contribute to achieving the best scores on the GSV test, reflecting minimal glare sensation. To achieve the best GSV scores, the following conditions should be met:

- Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G4 (solar low-e) or G7 (bronze solar low-e)
- Window/Screen Luminance Ratio (Lum3): in the range of 80 – 190
- Eye-Level Illuminance (EV3): over 400 lux

Table 4.29. Example of rules regarding the best GSV score

Input variables			**Output**
Glass type	*Lum3*	*EV3*	*GSV*
G2	100	500 lux	0.84
G4	80	400 lux	0.76
G7	120	600 lux	0.82

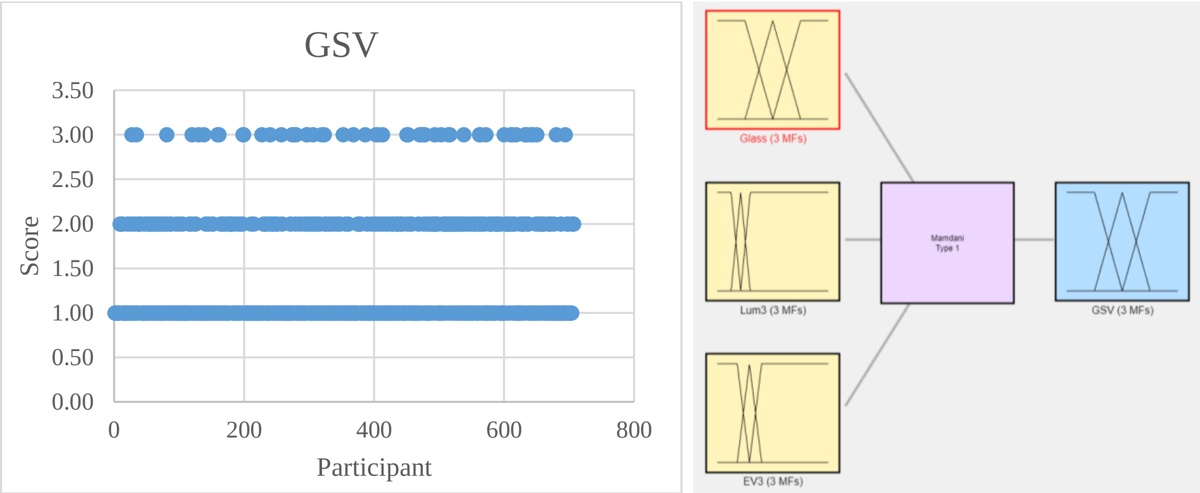


Figure 4.33. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for GSV

Figure 4.34 illustrates the fuzzy logic model used to predict visual comfort score in questionnaire based on specific variables. The model integrates input variables, including glass type, eye-level illuminance, and outdoor color temperature, to determine the best conditions for achieving visual comfort, as measured by the sum of Likert scale responses. A score of 15 or higher indicates optimal visual comfort. Table 4.30 details the rules established for achieving the highest visual comfort scores based on following input variables:

- Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G5 (smoked solar low-e), G6 (blue solar low-e) or G7 (bronze solar low-e)
- Eye-Level Illuminance (EV3): 260 lux and above
- Outdoor Color Temperature (CCT1): 6700K and above

Table 4.30. Example of rules regarding the best comfort score

Input variables			**Output**
Glass type	*EV3*	*CCT1*	*Comfort*
G7	300 lux	70000K	16.00
G6	550 lux	8500K	16.00
G5	750 lux	6700K	16.00

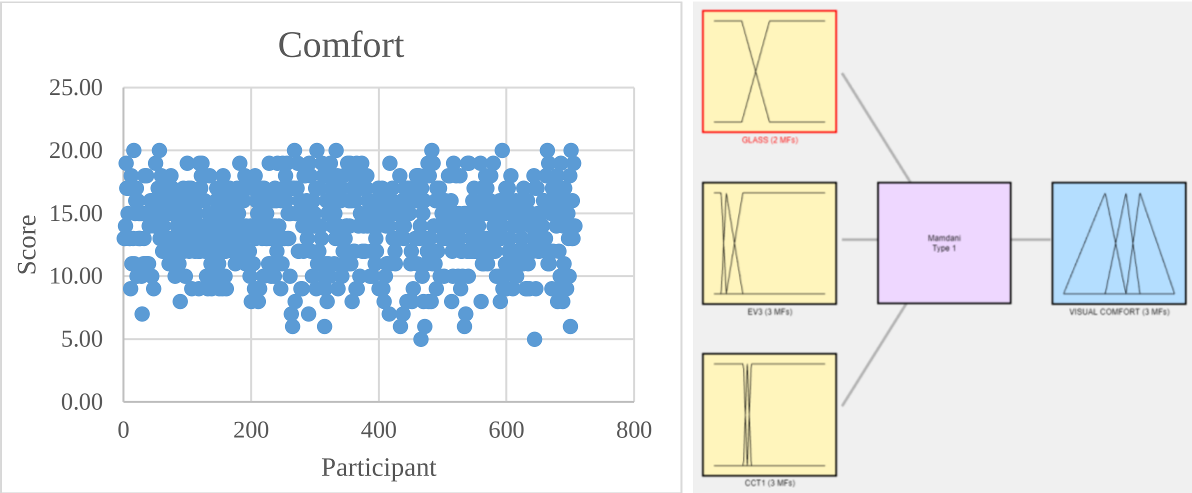


Figure 4.34. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for comfort

Figure 4.35 demonstrates the fuzzy logic model applied to predict naturalness ratings based on environmental variables. The model considers key input factors such as glass type, outdoor illuminance, and indoor color temperature. When the sum of the answers on the Likert scale is above 15, it indicates optimal lighting conditions in terms of perceived naturalness. Table 4.31 provides sample configurations that illustrate the input-output relationships used in the fuzzy logic model. The best naturalness score can be obtained when the following conditions are met:

- Glass type: G1 (clear glass), G3 (low-e), G4 (solar low-e) or 76 (bronze solar low-e)
- Outdoor Illuminance (EH2): 570 lux and above
- Indoor Color Temperature (CCT2): in the range of 3000K – 7000K

Table 4.31. Example of rules regarding the best naturalness score

Input variables			**Output**
Glass type	*EH2*	*CCT2*	*Naturalness*
G1	570 lux	6000K	16.60
G4	1000 lux	4000K	15.40
G7	750 lux	5500K	16.70

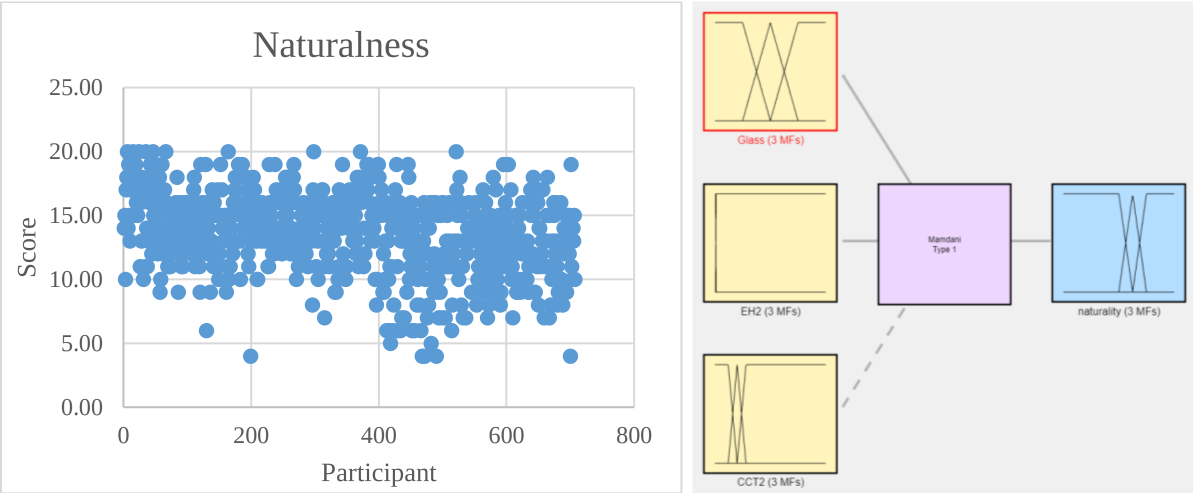


Figure 4.35. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for naturalness

Figure 4.37 showcases the fuzzy logic model designed to predict precision in lighting conditions, based on specific environmental variables. Precision refers to the clarity and sharpness perceived by participants, and a sum of responses over 30 on the Likert scale indicates the optimal lighting condition for precision. The model integrates key inputs such as glass type, Equivalent Melanopic Lux, and Indoor Spectral Power Distribution to generate precision scores. Table 4.33 provides sample input configurations that result in the best precision scores, and specific requirements are as follows:

- Glass type: G1 (clear glass), G2(smart glass), G6 (blue solar low-e) or G7 (bronze solar low-e)
- Equivalent Melanopic Lux (EML): 175 lux and above
- Indoor Spectral Power Distribution (SPD2): In the range of 0 – 485.70

Table 4.32. Example of rules regarding the best precision score

Input variables			**Output**
Glass type	*EML*	*SPD2*	*Precision*
G1	175 lux	480.50	39.40
G6	250 lux	485.70	39.50
G7	500 lux	478.00	39.50

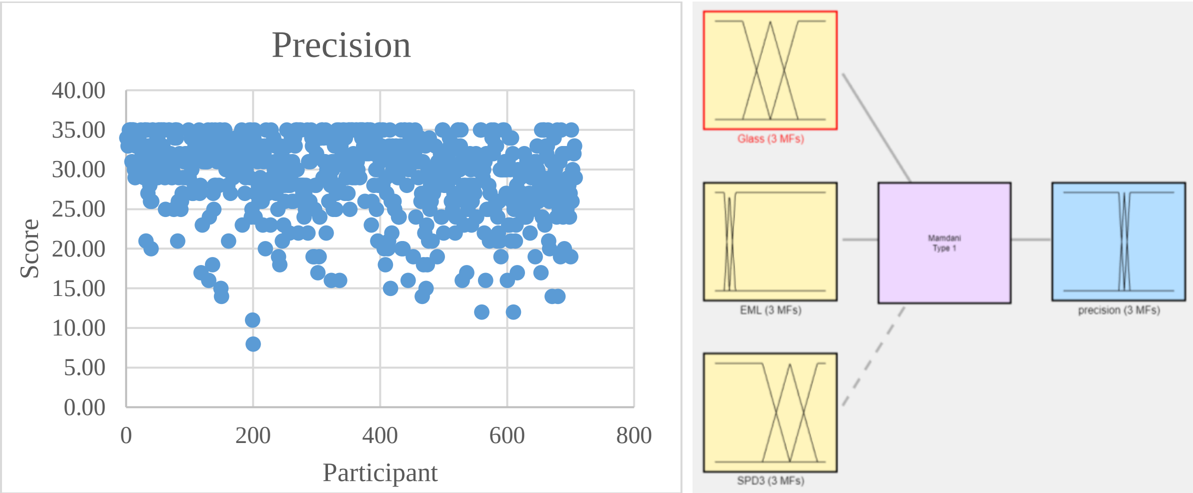


Figure 4.36. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for precision

Figure 4.47 illustrates the fuzzy logic model designed to predict user satisfaction with lighting conditions, based on specific environmental variables. A sum of responses over 20 on the Likert scale indicates optimal lighting conditions for user satisfaction. The model takes into account factors such as glass type, Equivalent Melanopic Lux, and outdoor color temperature to generate satisfaction scores. Accordingly, the best satisfaction score can be obtained for this category when the following conditions are met:

- Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G5 (smoked solar low-e, G6 (blue solar low-e) or G7 (bronze solar low-e)
- Eye-Level Illuminance (EV3): 260 lux and above
- Outdoor Color Temperature (CCT1): 6700K and above

The sample configurations in Table 4.33 demonstrate how various factors—particularly glass type and EML—are key in optimizing lighting conditions to ensure user satisfaction.

Table 4.33. Example of rules regarding the best satisfaction score

Input variables		**Output**
Glass type	*EML*	*Satisfaction*
G2	375 lux	20.00
G7	450 lux	20.00
G5	580 lux	20.00

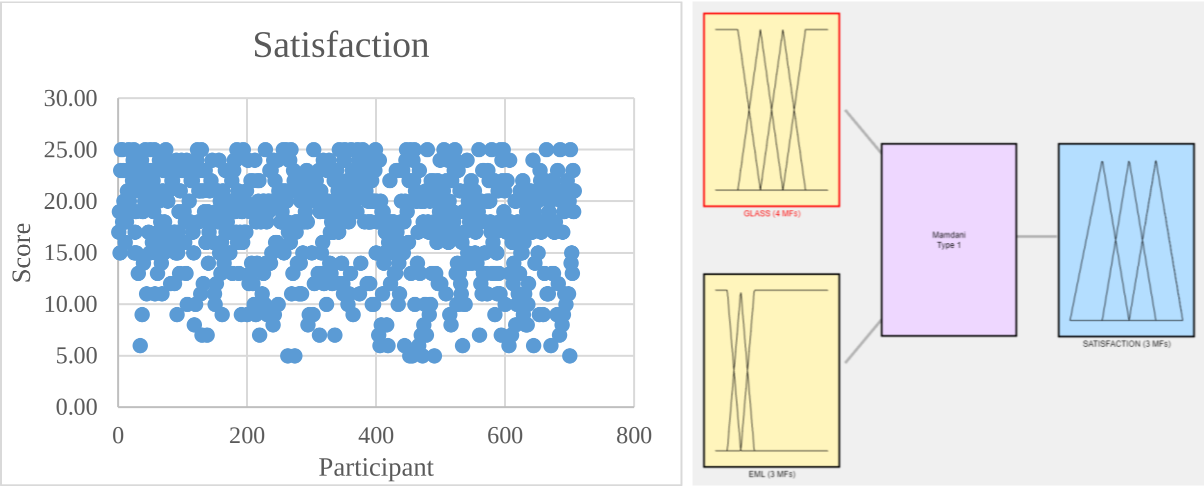


Figure 4.37. Scatterplot (a) and fuzzy logic model inputs and outputs (b) for satisfaction

The fuzzy logic models allows for the aggregation of these conditions to predict performance levels dynamically, recognizing that human sensory and cognitive responses are influenced by a spectrum of interdependent factors rather than isolated variables. By integrating these parameters into a Fuzzy Logic framework, the study effectively maps the complex interactions between environmental factors and human performance, offering insights into the optimal conditions for visual tasks in built environments.

CHAPTER 5

DISCUSSION

5.1. Discussion of Analyses with Existing Glazing

Efforts to achieve better lighting design for individuals' behaviours and experiences have intensified, considering the effects of lighting on humans. In this study, lighting conditions with standard existing glazing were initially considered. Using a dynamic LED lighting system, the study aimed to understand office users' lighting preferences (intensity, color temperature) and investigate changes in alertness, mood, task performance, and satisfaction compared to standard office lighting conditions. Experiments conducted in rooms facing north and south also observed the effects of different daylight characteristics on interior lighting and dynamic lighting preferences. Objective measurement results indicated that although different light characteristics dominated the rooms throughout the day, participants' preferences for LED lighting system settings did not change. In the second phase, where light settings were controllable, participants preferred working under brighter and warmer light (towards 4500K). There was no significant difference in CS and EML values, which affect people's biological rhythms. While the new adjustment of light conditions had a slight impact on subjective alertness, no change was observed in participants' mood. There was no correlation between attention and executive functions in task performance and lighting conditions (intensity, color temperature). However, short-term memory appeared to be related to eye-level lighting, with participants performing better under low lighting conditions (below 500 lux). Surveys incorporating participants' subjective evaluations revealed that the lighting conditions in the second phase (higher illumination, lower CT) were better in terms of visual comfort, naturalness, and satisfaction. This study, which raised awareness about human-centric lighting and guided participants to discover suitable conditions for themselves through dynamic lighting, suggests the use of a dynamic lighting system controllable by the user group in the office environment. Various lighting standards developed specifically for workplaces are mostly based on quantitative evaluations. However, the characteristics of light that people are exposed to can also affect visual performance, as well as work performance, health, and well-being. Therefore, it is essential to ensure psychological comfort conditions and user satisfaction to achieve more efficient working environments.

5.2. Discussion of Findings Regarding Different Glass Types

The impact of different glass types on indoor lighting conditions, especially in terms of illuminance, correlated color temperature (CCT), and spectral power distribution (SPD), reveals significant variations that are crucial for understanding the overall lighting quality and user experience.

The measurements conducted with clear glazing highlight the substantial differences in illuminance and CCT between the south-facing and north-facing rooms. The south-facing facade consistently received higher outdoor illuminance and exhibited more fluctuations throughout the day, reflecting its greater exposure to sunlight. However, despite these fluctuations, the north-facing facade demonstrated higher CCT values, indicating a persistent predominance of cooler light, which lasted longer in the day, creating a cooler indoor environment. These findings suggest that facade orientation and outdoor conditions significantly influence the lighting characteristics within a space.

Glass types yielded different results in both directions concerning the illuminance and CCT measured simultaneously with the SPDs. Measurements taken from the window reveal that the currently used clear glazing shows the trend closest to the southern sky SPDs, indicating that the glass behaves more neutrally compared to others. When examining SPDs across different glass types, smart glass, low-e glass, and solar low-e glass maintained relatively neutral behavior, minimally altering the daylight spectrum. This neutral filtering effect allowed for more accurate daylight transmission, preserving the natural characteristics of daylight indoors. In contrast, tinted solar low-e glasses (G5, G6, G7) and reflective glass (G10) modified the spectral distribution of daylight, particularly in the range of 520-650 nm, causing a notable increase in the energy released within this range. This shift towards higher wavelengths introduced a warmer light indoors, altering the visual appearance and possibly reducing the clarity of details. The most dramatic alterations were observed in photovoltaic (PV) glasses, with blue PV glass (G8) intensifying the cooler blue tones of daylight, peaking at 500 nm, while orange PV glass (G9) created a stark contrast by filtering out shorter wavelengths and emphasizing longer wavelengths around 570 nm, giving the indoor environment a reddish-orange hue. These changes in the spectral properties of daylight underscore the significant role that glass type plays in modifying the color and quality of natural light entering a space.

Illuminance levels also varied markedly across glass types. As expected, there was a significant reduction in illuminance when transitioning from outdoor to indoor environments due to the filtering effect of the glass. While orange PV glass allowed the highest outdoor illuminance, it significantly reduced indoor illuminance, especially at eye-level. Conversely, clear glass and smart glass maintained relatively high indoor illuminance levels, suggesting that these glass types are more effective at transmitting natural light. The variation in LED dimmer settings among glass types further reflects users' preferences for compensating for natural light with artificial lighting. Glass types like orange PV and reflective, which had higher outdoor illuminance, required higher dimmer settings to achieve satisfactory indoor brightness, indicating that even with high natural light, participants preferred brighter artificial lighting indoors, possibly due to uneven distribution or lower perceived quality of natural light. On the other hand, glass types that allowed more balanced natural light penetration, such as G1 and G6, required lower dimmer settings, suggesting these glass types provided more satisfactory natural lighting conditions.

CCT values also displayed interesting patterns across glass types. Indoor CCT values were generally lower than outdoor values due to the filtering effects of the glass, with some glass types like clear glass, solar low-e glass, and smoked solar low-e glass showing minimal changes between indoor and outdoor CCT, thereby maintaining a more neutral lighting environment. Smart glass and bronze solar low-e glass exhibited moderate decreases in CCT, indicating a slight cooling effect indoors. However, the most pronounced changes were observed in blue PV glass, where indoor CCT values remained significantly higher, indicating that cooler tones of light were either retained or even enhanced indoors. In contrast, orange PV glass resulted in extremely low indoor CCT values, producing a warm, almost orange indoor environment. This drastic shift highlights the significant impact of these specialized glass types on the color characteristics of indoor lighting.

Overall, the findings show that glass types play a pivotal role in shaping the indoor lighting environment by influencing not only illuminance levels but also the color temperature and spectral characteristics of daylight. Clear glass, smart glass, and solar low-e glass offer relatively neutral filtration, allowing for natural light to be transmitted indoors with minimal alteration. In contrast, tinted and photovoltaic glasses significantly modify the light spectrum, which can affect the perceived visual comfort and lighting quality indoors. These variations underscore the importance of selecting appropriate glass types in architectural design to balance natural daylight transmission with the need for artificial lighting to maintain optimal indoor lighting conditions.

5.3. Discussion of Findings Regarding CS and EML Values

Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) are essential indicators for assessing the impact of lighting on the human circadian system, influencing aspects such as mood, alertness, and overall health. The Lighting Research Centre recommends a CS value of 0.3 or higher to effectively stimulate the circadian system, while the WELL Standard suggests maintaining an EML value of 250 lux for at least four hours at eye level in workplaces. These thresholds provide a basis for evaluating the efficacy of different glass types and lighting conditions in meeting circadian health requirements.

In this study, both CS and EML values were measured across different glass types during two experimental stages, with dynamic LED lighting introduced in the second stage. The findings show that during the first stage, only clear glass and smart glass exceeded the CS and EML thresholds. Although low-e and reflective glass did not meet the CS thresholds, they were able to achieve at least 250 lux in EML values. However, dynamic LED lighting in the second stage significantly improved the performance of other glass types, such as low-e glass, bronze solar low-e, blue PV glass, and orange PV glass, which initially fell short of these thresholds. Neutral solar low-e glass, blue solar low-e glass, and smoked solar low-e glass remained below the threshold even with dynamic LED lighting. Orange PV glass, in particular, showed the most dramatic increase in CS an EML values, demonstrating that dynamic lighting can substantially improve circadian effectiveness. This improvement suggests that dynamic lighting can effectively compensate for suboptimal daylight conditions, helping to meet circadian thresholds across a broader range of glass types. Dynamic LED lighting also significantly enhances melanopic light exposure, especially when certain glass types would otherwise filter out much of the circadian-effective spectrum. This highlights the importance of both glass transmittance and the spectral properties of lighting in achieving optimal circadian lighting conditions.

The analyses performed in the study reveal the importance of certain illuminance and color temperature levels in achieving optimum CS and EML values. Circadian thresholds can be met when the illuminance are above 300 lux and LED color temperatures are above 4000K. In contrast, daylight alone or LED color temperatures below 4000K are insufficient for achieving the necessary circadian stimulus. This suggests that cooler, brighter lighting conditions are more effective in achieving the recommended circadian light levels, further emphasizing the importance of adequate lighting in promoting health and well-being.

In the study, a strong relationship was observed between the calculations of both CS and EML values. Although these two circadian indicators are measured using different methods, their results follow a similar pattern. Both indicators produced comparable outcomes under specific lighting conditions, with low or high values showing parallel trends. This suggests that the impact of both CS and EML on user task performance and subjective evaluations is similar. Additionally, EML values, in particular, were found to have a high correlation with eye-level illuminance. This indicates that the amount of light has a greater influence on circadian values than the spectral distribution of light.

5.4. Discussion of Findings Regarding Performance Tests

This section examines the relationship between lighting conditions and performance tests, integrating results from both objective measurements and subjective evaluations. The Landolt test, which assesses visual acuity, showed significant improvements in performance when participants were exposed to certain lighting conditions. Error rates were notably lower in the second stage of the experiment, suggesting that participants performed better under the self-adjusted lighting settings, particularly with higher indoor color temperatures (cooler light) and dominant wavelengths. These cooler light conditions increased contrast on the paper, allowing participants to distinguish details more effectively. Additionally, a positive correlation was found between glass type and Landolt test success; glasses with higher transmittance improved performance. Gender also played a role, with females performing better than males in this test. Furthermore, when Circadian Stimulus CS and EML values exceeded their recommended thresholds ($CS > 0.3$, $EML > 250$ lux), participants demonstrated significantly lower error rates, further confirming the positive impact of circadian-effective lighting on visual performance and accuracy.In the Stroop test, a computer-based test measuring reaction time, participants showed a statistically significant reduction in response time during the second stage of the experiment, reflecting improved performance under dynamic lighting. However, while circadian lighting positively impacted visual tasks, its influence on cognitive tasks like reaction time was less pronounced, as no significant correlation was found between CS and EML and Stroop test results. Age was an important factor, as response times increased with age, indicating slower reaction times for older participants. Similarly, the n-back test, which evaluates short-term memory and attention, showed limited effects from lighting conditions. While men performed better than women, and participants tended to perform better in the afternoon, the influence of lighting was less clear. A weak trend suggested that higher eye-level illuminance was associated with a decrease in correct matching rates, while increased outdoor illuminance and cooler light (higher color temperature) were linked to more incorrect matches. However, these effects were not statistically significant, indicating that lighting conditions may have less impact on computer–based tasks compared to paper-based ones. If we consider the overall task performance, lighting conditions, especially cooler light with higher contrast, significantly improved performance in visual tasks like the Landolt test. However, the effects of circadian lighting on computer-based tasks, such as the Stroop and n-back tests, were less pronounced, suggesting that visual tasks on paper are more sensitive to changes in lighting conditions.

Subjective evaluations provided further insights into participants' responses to lighting. GSV scores revealed that visual discomfort decreased as participants adjusted their lighting settings, with glass type having a notable influence on visual comfort. Participants reported feeling more comfortable and satisfied with their lighting environment when glass types and lighting adjustments better aligned with their preferences. When analysing the subjective evaluations of lighting quality and satisfaction, several key factors emerge as influential in participants' responses. The experimental stage plays a significant role in shaping participants' assessments of visual comfort, including comfort, homogeneity, and overall light quality. Glass types particularly affect the evenness of light distribution, with certain types allowing more uniform lighting conditions. Additionally, unlike eye-level CCTs, illuminance significantly impact perceptions of glare and visual comfort, where higher illuminance tend to improve participants' visual comfort. The correlated color temperature also plays a critical role in determining how participants perceive the visual environment. Higher CCT values, often associated with cooler light, are more likely to be rated as attractive, with spectral distribution acting as another key determinant in this perception. The naturalness of the visual environment is strongly tied to the lighting conditions, with participants feeling more in tune with natural light under certain settings. Notably, satisfaction with the outside view varies significantly depending on room orientation, emphasizing the influence of natural light exposure. As the experiment progressed and illuminance and color temperatures fluctuated, a clear relationship emerged between the quality of artificial lighting and how participants perceived the textures and forms of objects. While glass types also affected these variables, their influence was slightly less pronounced. Participants' color perception in the room was marginally influenced by changes in stages, eye-level CCTs, and SPD measurements. Precision assessments, which gauge how well participants could read text, see details, and discern contrasts, revealed that the permeability of the glass had a substantial impact on readability, contrast balance, and impressions of texture. In terms of subjective evaluations of overall lighting quality, participants considered aspects such as color saturation, the light's ambiance, whether the light felt natural or artificial, and whether the lighting level was appropriate for working conditions. These factors were significantly influenced by the type of glass, particularly in terms of how participants perceived work efficiency and overall satisfaction. Glass types that least altered the spectral properties and light levels in the room led to higher evaluations of overall lighting quality. Objective and subjective results together show that glass types affect not only the artificial lighting preferences but also users' health, work efficiency, and overall satisfaction.

The subjective evaluations confirmed the positive impact of circadian-effective lighting. When lighting conditions met or exceeded the circadian stimulus thresholds, participants reported improved mood, comfort, and satisfaction. Positive affect (PA) scores increased significantly when CS was above 0.3 and EML exceeded 250 lux, while negative affect (NA) scores decreased. Furthermore, participants felt more visually comfortable and satisfied under these conditions, with significant improvements in perceptions of naturalness and precision. These findings emphasize that lighting conditions optimized for circadian health not only enhance performance but also improve participants' overall well-being and satisfaction with their environment.

5.5. Determination of Optimal LED Lighting and Glass Types

This section discusses the determination of the most suitable LED lighting condition and glass type, along with the relationship between lighting measurement and performance tests. The findings of the study reveal that users' LED dimmer and color temperature preferences vary significantly based on the transmittance and color characteristics of the glass types. Across all glass types, participants tended to adjust the LED lighting to achieve neutral color temperatures (approx. 4600K) and illumination between 300-500 lux at eye-level. These preferences correspond to approximately 450-650 lux and a color temperature around 4800K at the workplane. However, these optimal lighting conditions could not be fully achieved with the dominant color properties of orange PV and blue PV glass. Despite LED adjustments, blue PV glass resulted in a predominantly cold light, while orange PV glass produced a dominant warm light. Consequently, these glass types consistently received the lowest scores across all subjective evaluation categories, including comfort, naturalness, precision, and satisfaction.

When considering user satisfaction, clear glass, solar low-e glass, and bronze solar low-e glass emerged as the best options. These glass types provided better light transmission while preserving daylight's natural characteristics, leading to higher satisfaction ratings in subjective evaluations. Reflective glass and tinted solar low-e glass, while altering the daylight spectrum slightly, performed moderately well but resulted in more varied subjective responses. However, orange PV and blue PV glass, due to their strong color distortion of natural daylight, should be considered the least favorable choices if user satisfaction is prioritized. It is recommended that these glass types not be used without dynamic LED lighting, as their color-altering effects significantly reduce satisfaction.

In terms of circadian lighting indicators such as CS and EML, clear and smart glass were able to meet the required thresholds even without LED lighting. This suggests that these glass types allow enough natural light penetration to stimulate the circadian system effectively. However, low-e glass, bronze solar low-e glass, blue PV glass, and orange PV glass could only achieve the necessary CS and EML values with the assistance of dynamic LED lighting. This highlights the importance of LED lighting to compensate for the lower transmittance and altered spectral properties of these glass types.

Performance test results further support these findings. For paper-based tasks, such as the Landolt test, participants performed best with high-transmittance, low-color-distortion glass types like clear, smart, and low-e glass. These glass types allowed for higher contrast and better visual clarity, enhancing task performance. However, for computer-based tasks, performance was more closely tied to demographic variables such as age and gender than to lighting conditions. In particular, lower transmittance glass types that did not significantly alter the color characteristics of daylight, such as solar low-e and reflective glasses, led to lower performance in paper-based tasks but improved performance in computer-based tasks. Given these results, it is recommended that glass selection prioritize performance in paper-based tasks, as these are more directly influenced by lighting conditions. Clear, smart, and low-e glass types are optimal for environments requiring high visual clarity and task performance. In contrast, glass types with both low transmittance and significant color distortion of daylight, such as orange PV and blue PV glass, should be avoided in settings where both visual and cognitive task performance are critical.

In summary, the optimal glass type for most environments is one that maintains high transmittance and neutral color properties, such as clear, smart, or solar low-e glass. These glass types not only ensure high user satisfaction but also support the necessary circadian light levels, task performance, and visual comfort. In building design, if tinted or coated glass is preferred for various reasons, dynamic LED lighting can effectively compensate for the negative effects caused by their low transmittance and distinct color characteristics, but glass selection should still prioritize maintaining the natural characteristics of daylight. These findings can guide lighting designers in selecting fixture color temperature and light intensity based on the type of glass used in the building facade. Evaluations of lighting quality reveal strong relationships between light homogeneity, the harmony of natural and artificial light, perceived textures and colors of objects, contrast balance between paper and surroundings. Regarding overall evaluations of visual comfort, naturalness, sensitivity, and lighting quality in the room, clear glass is the most satisfactory, while tinted PV glasses score the lowest in the performance tests. The ability to change room light settings based on glass type has increased overall satisfaction. This highlights the importance of considering glass selection alongside dynamic LED systems in lighting design, a fundamental aspect of user well-being, work performance, and satisfaction in workplaces.

CHAPTER 6

CONCLUSION

In recent literature, human-centric lighting is defined as a set of technical methods designed to replicate the biological effects of daylight in artificial lighting environments (Houser and Esposito 2021). Metrics such as Circadian Stimulus (CS) and Equivalent Melanopic Lux (EML) have been developed to measure the non-visual effects of light, which are thought to influence individuals' work performance, attention, and mood. However, these metrics are fundamentally rooted in numeric measurements like illuminance and spectrum. This study approaches human-centric lighting by examining both work performance and subjective evaluations within the context of these metrics. The results showed that only paper-based performance tests demonstrated significant differences aligned with circadian stimulation threshold values, as identified in the literature. In contrast, computer-based cognitive tests did not reflect any notable effects from circadian metrics. However, subjective assessments such as alertness, visual comfort, naturalness, and clarity exhibited significant variations according to circadian threshold values. This highlights the importance of considering not only objective task performance but also subjective impressions of the workspace, as both contribute to productivity and efficiency in working environments. This study suggests that achieving human-centric lighting requires more than focusing solely on circadian metrics like CS and EML. It is also essential to take into account broader subjective evaluations, as they play a critical role in user satisfaction and overall workspace quality. Therefore, this research proposes an expanded definition of human-centric lighting: a set of technical methods aimed not only at replicating the biological effects of daylight in artificial settings but also at enhancing user satisfaction and well-being.

Despite meeting the required numerical lighting levels defined in standards, individual preferences and choices may vary. Various studies have demonstrated a link between cognitive performance and lighting conditions. In this study, both task performance and subjective evaluation categories were established to define criteria for human-centric lighting design. This approach can be considered in the early design phases by architects, lighting designers, or building performance evaluation systems. Accordingly, Landolt, Stroop, and N-back tests were grouped into one category, while comfort, naturalness, precision, satisfaction, and GSV tests were placed in another category. A third category addressed alertness and mood assessments. Through fuzzy logic methods, the criteria required for each of these three performance categories were determined. These criteria are summarized in Table 6.1. When considering each of these categories, achieving the optimal performance is viewed as a positive factor in lighting design. Achieving the highest performance group in any of the Landolt, Stroop, or N-back tests grants +1 point; achieving the highest performance group in any of the comfort, naturalness, precision, satisfaction, or GSV tests also earns +1 point; and the same applies for alertness and mood assessments. For example, when certain glass types (G1, G2, or G3) are used, and lighting conditions with a CS value between 0.15 and 0.40 and an indoor color temperature between 0 and 5000K are provided, the error rate in the Landolt test is minimized, resulting in the best performance. When the necessary criteria for any performance test are met, one can earn an additional point in the task performance category.

The overall result of the study showed that both objective and subjective data collection methods were able to contribute holistically to both statistical and artificial intelligence models. Although the prediction percentages of artificial neural networks were moderate in terms of performance indicators, they were acceptable due to the predictive nature of subjective, human-based data and evaluations. The predictive estimation of subjective evaluations resulted in more successful prediction rates. Classification was achieved by establishing fuzzy logic models. In this context, it can be said that the methodology of this study was successful and will be guiding for future studies. Over the past 30 years, we have witnessed the development of human-centric lighting, including the initial efforts related to the visual and biological effects of LED lighting. Subsequently, researchers noticed similar effects of daylight and integrated lighting systems, leading to the creation of thoughts on lighting design to ensure people's health and well-being alongside new lighting standards. Conventional lighting design aims to meet specific glare ratios for horizontal workplane illuminance necessary for visual performance and/or brightness control for visual comfort. Recently, researchers and lighting companies have witnessed the development of knowledge about the non-visual effects of light on people and have contributed to the emergence of circadian lighting design. Thus, the standard approach to lighting design has evolved into a human-centric approach. More comprehensive research on circadian metrics, energy efficiency, and sustainable lighting requirements is expected to be conducted in the future. It is believed that this study will guide researchers with its necessary knowledge infrastructure and working methodology in line with these thoughts.

Table 6.1. Criteria for optimal performance in task performance, user satisfaction, and mood/alertness categories based on lighting conditions

Category	Threshold	Criteria	Point
Task performance	Landolt (error rate): below 30%	Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e)	+1
		Circadian Stimulus (CS): in the range of 0.15 – 0.30 or 0.30 – 0.40	
		Indoor Color Temperature (CCT2): in the range of 0-5500K	
	Stroop (reaction time): below 800 ms	Glass type: G2 (smart glass), G3 (low-e), G4 (solar low-e) or (G5) smoked solar low-e	
		Eye-Level Illuminance (EV3): in the range of 200 – 350 lux	
		Indoor Color Temperature (CCT2): in the range of 5100K – 6700K	
	N-back (correct matches): above 80%	Equivalent Melanopic Lux (EML): above 300 lux	
User Satisfaction	Visual comfort: above 15	Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G5 (smoked solar low-e), G6 (blue solar low-e) or G7 (bronze solar low-e)	+1
		Eye-Level Illuminance (EV3): above 260 lux	
		Outdoor Color Temperature (CCT1): above 6700K	
	Naturalness: above 15	Glass type: G1 (clear glass), G3 (low-e), G4 (solar low-e) or 76 (bronze solar low-e)	
		Outdoor Illuminance (EH2): 570 lux and above	
		Indoor Color Temperature (CCT2): in the range of 3000K – 7000K	
	Precision: above 30	Glass type: G1 (clear glass), G2(smart glass), G6 (blue solar low-e) or G7 (bronze solar low-e)	
		Equivalent Melanopic Lux (EML): 175 lux and above	
		Indoor Spectral Power Distribution (SPD2): In the range of 0 – 485.70	
	Satisfaction: above 20	Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G5 (smoked solar low-e, G6 (blue solar low-e) or G7 (bronze solar low-e)	
		Eye-Level Illuminance (EV3): 260 lux and above	
		Outdoor Color Temperature (CCT1): 6700K and above	
	GSV: 1 (imperceptible)	Glass type: G1 (clear glass), G2 (smart glass), G3 (low-e), G4 (solar low-e) or G7 (bronze solar low-e)	
		Window/Screen Luminance Ratio (Lum3): in the range of 80 – 190	
		Eye-Level Illuminance (EV3): over 400 lux	
Alertness and Mood	KSS: 1, 2, 3 (alert)	Glass type: clear glass, smart glass, low-e or bronze solar low-e	+1
		LED Dimmer setting: in the range of %45 – %100	
		Equivalent Melanopic Lux (EML): above 250 lux	
	PANAS: above 60	Glass type: clear glass or bronze solar low-e	
		LED Dimmer setting: 70% and above	

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APPENDICES

APPENDIX A. MEASUREMENT DATA COLLECTION SHEETS

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

KUZEY ODA ÖLÇÜM KAĞIDI

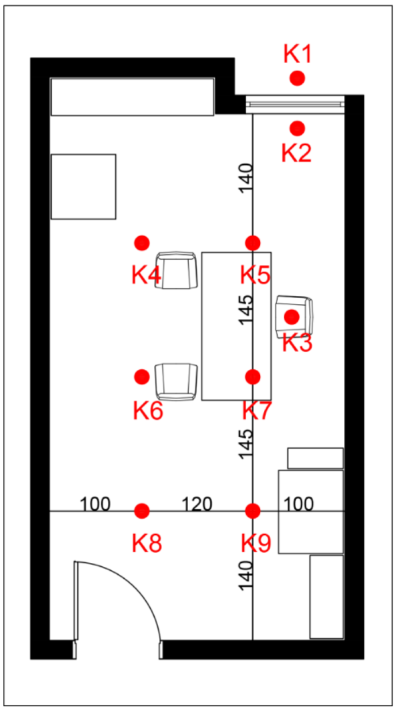
Görevli:

Katılımcı Kodu: **Tarih/saat:**

Cam Türü:
- C1 Mevcut Durum ☐
- C2 Akıllı Cam ☐
- C3 Nötral solar low-e 50/33 ☐
- $C4_K$ Nötral ısı kontrol 71/53 ☐
- C5 Füme solar low-e ☐
- C6 Mavi solar low-e ☐
- C7 Bronz solar low-e ☐

Hava Durumu: Güneşli ☐ Bulutlu☐ Parçalı Bulutlu☐

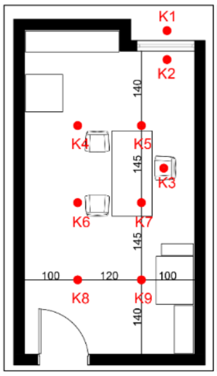
DIŞ ORTAM ÖLÇÜMLERİ		
Güneş Yüksekliği		
Güney Açısı		
İç Hava Sıcaklığı	$T_{iç}$	
Dış Hava Sıcaklığı	$T_{dış}$	
Dış Ortam Yatay Aydınlık Düzeyi	E_{H1}	
Dış Ortam Renk Sıcaklığı	CCT_1	
SPD yatay (pencere açıkken)	SPD_1	
İç Ortam Yatay Aydınlık Düzeyi	E_{H2}	
İç Ortam Renk Sıcaklığı	CCT_2	
SPD yatay (pencere kapalıyken)	SPD_2	
Parıltı Değeri (pencere açıkken)	L_{out}	
Parıltı Değeri (pencere kapalıyken)	L_{in}	
Camın Geçirgenlik Değeri (L_{in} / L_{out})	*t* (%)	

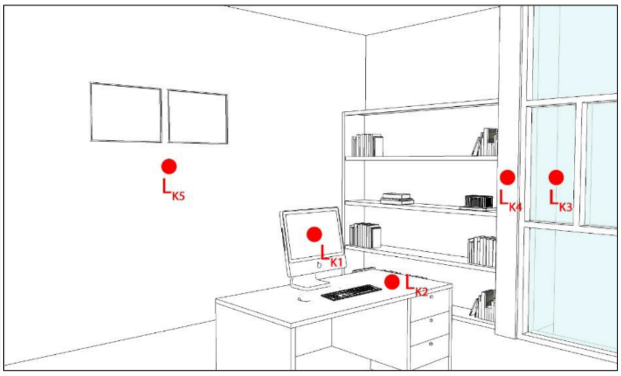


1

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

KUZEY ODA ÖLÇÜM KAĞIDI – İLK AŞAMA





LED AYARI: **Dimmer (%):** **Color Temp. (K):**

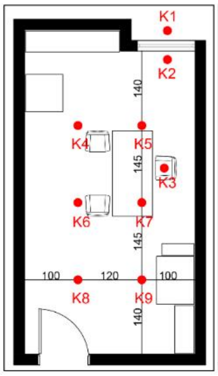
PARILTI ÖLÇÜMLERİ			
L_1		L_2	
L_3		L_4	
L_5			

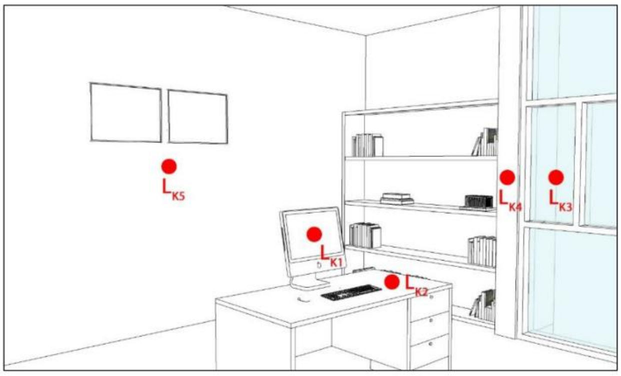
GÖZ HİZASI ÖLÇÜMLERİ		
Düşey Aydınlık Düzeyi	E_{V3}	
Renk Sıcaklık Değeri	CCT_3	
Spektral Güç Dağılımı (SPD)	SPD_3	

İÇ ORTAM ÖLÇÜMLERİ					
	Yatay aydınlık Düzeyi (E)		Renk Sıcaklık Değeri (CCT)		Spektral Güç Dağılımı (SPD)
E_{H4}		CCT_4		SPD_4	
E_{H5}		CCT_5		SPD_5	
E_{H6}		CCT_6		SPD_6	
E_{H7}		CCT_7		SPD_7	
E_{H8}		CCT_8		SPD_8	
E_{H9}		CCT_9		SPD_9	

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

KUZEY ODA ÖLÇÜM KAĞIDI – İKİNCİ AŞAMA





LED AYARI: **Dimmer (%):** **Color Temp. (K):**

PARILTI ÖLÇÜMLERİ			
L_1		L_2	
L_3		L_4	
L_5			

GÖZ HİZASI ÖLÇÜMLERİ		
Düşey Aydınlık Düzeyi	E_{V3}	
Renk Sıcaklık Değeri	CCT_3	
Spektral Güç Dağılımı (SPD)	SPD_3	

İÇ ORTAM ÖLÇÜMLERİ					
	Yatay aydınlık Düzeyi (E)		Renk Sıcaklık Değeri (CCT)		Spektral Güç Dağılımı (SPD)
E_{H4}		CCT_4		SPD_4	
E_{H5}		CCT_5		SPD_5	
E_{H6}		CCT_6		SPD_6	
E_{H7}		CCT_7		SPD_7	
E_{H8}		CCT_8		SPD_8	
E_{H9}		CCT_9		SPD_9	

3

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

GÜNEY ODA ÖLÇÜM KAĞIDI

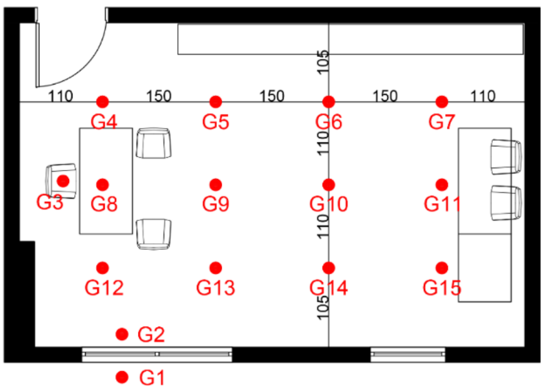
Görevli:

Katılımcı Kodu: **Tarih/saat:**

Cam Türü:

- C1 Mevcut Durum ☐
- C2 Akıllı Cam ☐
- C3 Nötral solar low-e 50/33 ☐
- C4G Tentasol mavi reflektif ☐
- C5 Füme solar low-e ☐
- C6 Mavi solar low-e ☐
- C7 Bronz solar low-e ☐
- C8 Fotovoltaik-Mavi ☐
- C9Fotovoltaik-Turuncu ☐

Hava Durumu: Güneşli ☐ Bulutlu☐ Parçalı Bulutlu☐

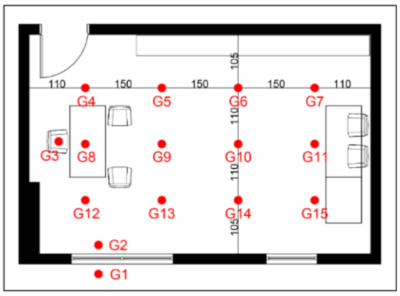


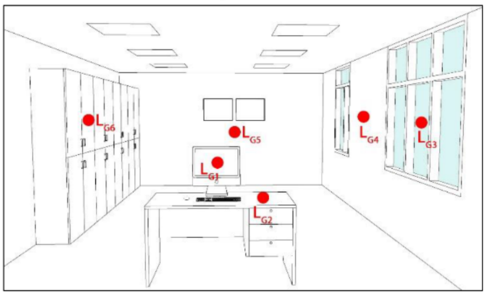
DIŞ ORTAM ÖLÇÜMLERİ					
Güneş Yüksekliği			Güney Açısı		
Dış Hava Sıcaklığı	$T_{dış}$		İç Hava Sıcaklığı	$T_{iç}$	
Dış Ortam Yatay Aydınlık Düzeyi	E_{H1}		İç Ortam Yatay Aydınlık Düzeyi	E_{H2}	
Dış Ortam Renk Sıcaklığı	CCT_1		İç Ortam Renk Sıcaklığı	CCT_2	
SPD yatay (pencere açıkken)	SPD_1		SPD yatay (pencere kapalıyken)	SPD_2	
Parıltı Değeri (pencere açıkken)	L_{out}		Parıltı Değeri (pencere kapalıyken)	L_{in}	
Camın Geçirgenlik Değeri (L_{in} / L_{out})	*t* (%)				

1

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

GÜNEY ODA ÖLÇÜM KAĞIDI – İLK AŞAMA





LED AYARI: Dimmer (%): Color Temp. (K):

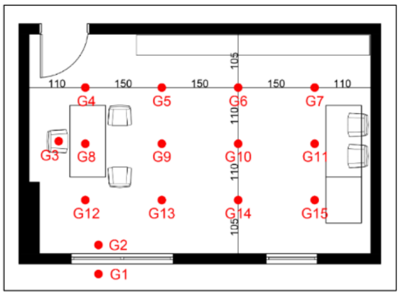
PARILTI ÖLÇÜMLERİ			
L_1		L_2	
L_3		L_4	
L_5		L_6	

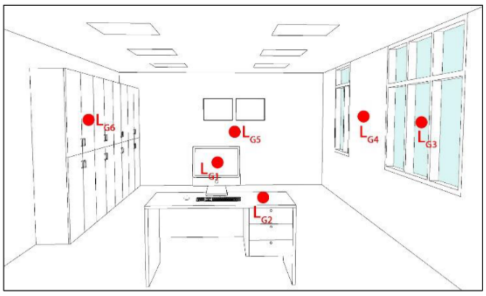
GÖZ HİZASI ÖLÇÜMLERİ		
Düşey Aydınlık Düzeyi	E_{V3}	
Renk Sıcaklık Değeri	CCT_3	
Spektral Güç Dağılımı (SPD)	SPD_3	

İÇ ORTAM ÖLÇÜMLERİ					
	Yatay Aydınlık Düzeyi (E)		Renk Sıcaklık Değeri (CCT)		Spektral Güç Dağılımı (SPD)
E_{H4}		CCT_4		SPD_4	
E_{H5}		CCT_5		SPD_5	
E_{H6}		CCT_6		SPD_6	
E_{H7}		CCT_7		SPD_7	
E_{H8}		CCT_8		SPD_8	
E_{H9}		CCT_9		SPD_9	
E_{H10}		CCT_{10}		SPD_{10}	
E_{H11}		CCT_{11}		SPD_{11}	
E_{H12}		CCT_{12}		SPD_{12}	
E_{H13}		CCT_{13}		SPD_{13}	
E_{H14}		CCT_{14}		SPD_{14}	
E_{H15}		CCT_{15}		SPD_{15}	

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

GÜNEY ODA ÖLÇÜM KAĞIDI – İKİNCİ AŞAMA





LED AYARI: **Dimmer (%):** **Color Temp. (K):**

PARILTI ÖLÇÜMLERİ			
L_1		L_2	
L_3		L_4	
L_5		L_6	

GÖZ HİZASI ÖLÇÜMLERİ		
Düşey Aydınlık Düzeyi	E_{V3}	
Renk Sıcaklık Değeri	CCT_3	
Spektral Güç Dağılımı (SPD)	SPD_3	

İÇ ORTAM ÖLÇÜMLERİ					
	Yatay Aydınlık Düzeyi (E)		Renk Sıcaklık Değeri (CCT)		Spektral Güç Dağılımı (SPD)
E_{H4}		CCT_4		SPD_4	
E_{H5}		CCT_5		SPD_5	
E_{H6}		CCT_6		SPD_6	
E_{H7}		CCT_7		SPD_7	
E_{H8}		CCT_8		SPD_8	
E_{H9}		CCT_9		SPD_9	
E_{H10}		CCT_{10}		SPD_{10}	
E_{H11}		CCT_{11}		SPD_{11}	
E_{H12}		CCT_{12}		SPD_{12}	
E_{H13}		CCT_{13}		SPD_{13}	
E_{H14}		CCT_{14}		SPD_{14}	
E_{H15}		CCT_{15}		SPD_{15}	

APPENDIX B. THE WRITTEN FORM USED DURING THE EXPERIMENTS

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
TÜBİTAK MAG 220M006 NOLU ARAŞTIRMA PROJESİ

Görevli:

Katılımcı Kodu: Tarih/saat:

IŞIĞIN İNSAN ÜZERİNDEKİ GÖRSEL OLMAYAN ETKİLERİ İÇİN PERFORMANS (SUBJEKTİF) TESTLERİ VE ANKET

Bu çalışma, İYTE Mimarlık Bölümü öğretim üyesi Prof. Dr. Z. Tuğçe Kazanasmaz tarafından yürütülen "Ofis kullanıcılarının bilişsel/çalışma performansları, beğenileri ve duygu durumlarının en uygun pencere camı optik özellikleri ve dinamik LED aydınlatmaya göre ilişkilendirilmesi ve sınıflandırılması" başlıklı Tübitak 220M006 nolu 1001 projesi ve aynı zamanda doktora öğrencisi ve proje bursiyeri F.Büşra Köse 'nin doktora tezi kapsamında yapılmaktadır.

1.1. KSS (KAROLINSKA UYKULULUK ÖLÇEĞİ)- İLK AŞAMA

Lütfen anketten 5 dakika önceki uyku durumunuzu değerlendirerek uygun açıklamayı daire içine alın.

Ölçek Değeri	Karolinska Uykululuk Ölçeği
1	Son derece uyanık
2	Gayet uyanık
3	Uyanık
4	Oldukça uyanık
5	Ne uykulu ne uyanık
6	Uyuşukluk belirtileri var
7	Uykulu ancak uyanık kalmak için herhangi bir çabası yok
8	Uykulu ancak uyanık kalmak için bazı çabalar göstermekte
9	Son derece uykulu

Eposta adresi:______________________________ 1

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
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1.2. PANAS (POZITIF VE NEGATIF DUYGU DURUM ÖLÇEĞİ)

Lütfen duygu durum kelimelerinden size en uygun olanını işaretleyiniz.

Nasıl hissettiğinizi belirtin.		Çok az veya hiç	Biraz	Orta derecede	Oldukça	Çok fazla
Panas 1	İlgili	☐	☐	☐	☐	☐
Panas 2	Sıkıntılı	☐	☐	☐	☐	☐
Panas 3	Heyecanlı	☐	☐	☐	☐	☐
Panas 4	Mutsuz	☐	☐	☐	☐	☐
Panas 5	Güçlü	☐	☐	☐	☐	☐
Panas 6	Suçlu	☐	☐	☐	☐	☐
Panas 7	Ürkmüş	☐	☐	☐	☐	☐
Panas 8	Düşmanca	☐	☐	☐	☐	☐
Panas 9	Hevesli	☐	☐	☐	☐	☐
Panas 10	Gururlu	☐	☐	☐	☐	☐
Panas 11	Asabi	☐	☐	☐	☐	☐
Panas 12	Uyanık	☐	☐	☐	☐	☐
Panas 13	Utanmış	☐	☐	☐	☐	☐
Panas 14	İlhamlı	☐	☐	☐	☐	☐
Panas 15	Sinirli	☐	☐	☐	☐	☐
Panas 16	Kararlı	☐	☐	☐	☐	☐
Panas 17	Dikkatli	☐	☐	☐	☐	☐
Panas 18	Tedirgin	☐	☐	☐	☐	☐
Panas 19	Aktif	☐	☐	☐	☐	☐
Panas 20	Korkmuş	☐	☐	☐	☐	☐

Puanlama:

Pozitif Duygu Durum (PDD):_________ Negatif Duygu Durum (NDD): _________

Eposta adresi:____ 2

1.3. LANDOLT HALKALARI TESTİ

Lütfen 2 dk içerisinde her yön için halka sayısını olabildiğince çabuk ve halkaları işaretlemeden sayın. Her yön için toplam halka sayılarını aşağıdaki boşluğa yazın.

Eposta adresi:____ 3

1.4. STROOP TEST

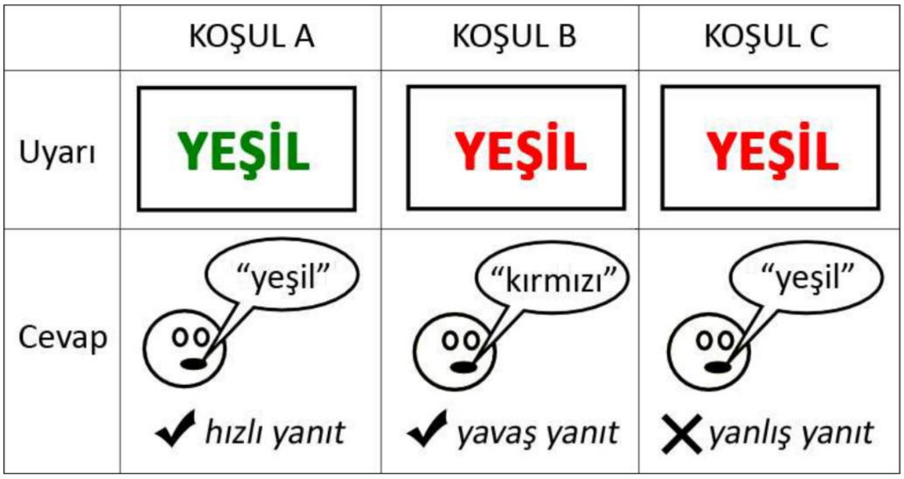
Lütfen ekranda gösterilecek renk isimlerinin mürekkep rengine göre mümkün olduğunca hızlı ve doğru bir şekilde yanıt veriniz ve klavyedeki ilgili düğmeye basınız.

Örneğin;

Yeşil için	**"Y"**	tuşuna basın.
Sarı için	**"S"**	tuşuna basın.
Kırmızı için	**"K"**	tuşuna basın.
Mavi için	**"M"**	tuşuna basın.

Rengin yazılışı ile mürekkep renginin tutarsız olması testi zorlaştırmaktadır. Başlamadan önce parmaklarınızı klavyedeki ilgili tuşların üzerine yerleştirin.

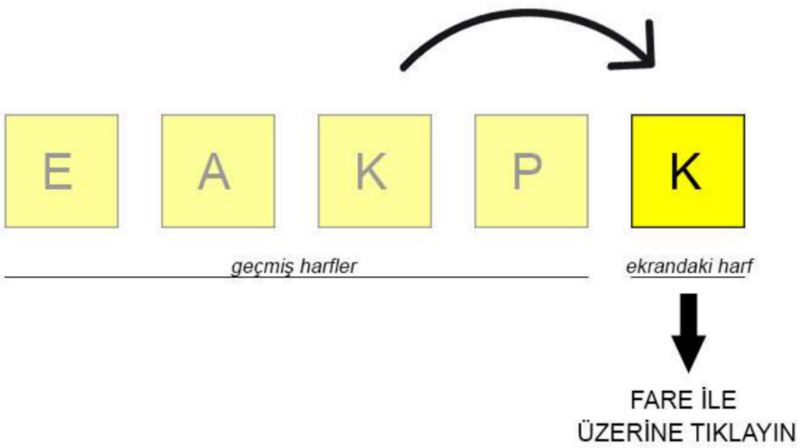
Örnek:



1.5. KISA SÜRELİ HAFIZA TESTİ (N-GERİ GÖREVİ)

Test sırasında bilgisayar ekranının ortasında art arda çeşitli harfler sunulacaktır. Her harf birkaç saniye gösterilir. Yalnızca gördüğünüz harf, iki geride gördüğünüz harfle eşleşiyorsa fare ile harfin üzerine tıklayınız. Aksi takdirde, hiçbir şey yapmayın. Yani bu bir n=2 geri görevidir.

Örneğin aşağıdaki dizide, yalnızca ikinci K'yi gördüğünüzde fareye tıklamalısınız:



Test 3 aşamadan oluşmaktadır. İlk aşamada görevi öğrenmenize yardımcı olmak için daha önce gördüğünüz harfler size hatırlatılacaktır.

Sonraki iki aşamada artık önceki harfler gösterilmeyecektir ve hepsini hafızanıza göre yapmanız gerekecektir.

Eposta adresi:____

1.6. ANKET

Lütfen odadaki aydınlatma koşullarını değerlendiriniz.

Görsel Konfor – Aydınlık Seviyesi							
Odadaki ışık	Karanlık	1	2	3	4	5	Parlak
Görsel olarak	Göz kamaştırıcı	1	2	3	4	5	Konforlu
Işık miktarı	Değişken	1	2	3	4	5	Homojen
Odadaki ışık	Sıkıcı	1	2	3	4	5	İlgi çekici
Doğallık							
Odadaki ışık	Yapay	1	2	3	4	5	Doğal
Nesnelerin dokuları ve görünüşleri	Farklı	1	2	3	4	5	Orijinal
Pencereden görülen dış ortam ve unsurlar	Yapay	1	2	3	4	5	Doğal
Odadaki renk sıcaklığı	Soğuk	1	2	3	4	5	Sıcak
Netlik							
Ekrandaki yazılar	Okunaksız	1	2	3	4	5	Okunaklı
Anketteki yazılar	Okunaksız	1	2	3	4	5	Okunaklı
Harfler ve kağıt arasındaki kontrast	Kötü	1	2	3	4	5	İyi
Nesnelerin dokuları ve görünüşleri	Bulanık	1	2	3	4	5	Net
Nesnelerin detayları	Görünmez	1	2	3	4	5	Görünür
Odadaki renkler	Tanımsız	1	2	3	4	5	Tanımlı
Pencereden görülen dış ortam ve unsurlar	Belirsiz	1	2	3	4	5	Belirgin
Memnuniyet							
Odadaki renkler	Soluk	1	2	3	4	5	Canlı
Işığın yarattığı atmosfer	Depresif	1	2	3	4	5	Keyifli
Odadaki doğal ve yapay ışık	Uyumsuz	1	2	3	4	5	Uyumlu
Odadaki ışık çalışmaya	Elverişsiz	1	2	3	4	5	Elverişli
Odanın genel aydınlatma kalitesi	Kötü	1	2	3	4	5	İyi

Eposta adresi:____ 6

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
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1.7. GÖRSEL RAHATSIZLIĞIN ÖZNEL HİSSİ

Lütfen görsel konforsuzluk (kamaşma) hissiyatınızı işaretleyiniz.

☐ 1. belli belirsiz ☐ 2. farkedilebilir ☐ 3. rahatsız edici ☐ 4. dayanılmaz

Eposta adresi:____ 7

İYTE MİMARLIK FAKÜLTESİ MİMARLIK BÖLÜMÜ DOKTORA PROGRAMI
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KİŞİSEL BİLGİLER:

Yaş:____________

Cinsiyet:___________

Meslek: _____________

Ortam ısısından memnun musunuz?	Memnun değil	1	2	3	4	5	Memnun
Dış hava koşullarından memnun musunuz?	Memnun değil	1	2	3	4	5	Memnun

Görme için kullanılan yardımcı elemanlar:

☐ gözlük ☐ lens ☐ kullanmıyorum ☐ diğer(açıklayın).

Göz kusurları: miyop, hipermetrop, astigmat, kusur yok, diğer (açıklayın)**:**_________

Kaç saat uyku uyudunuz: ____

Yemek yeme durumu: ____

☐Kahvaltı ☐ öğle yemeği ☐ ara öğün ☐ çay/kahve ☐ diğer

Anket veya teslerle ilgili eklemek istediğiniz bir yorum veya açıklama olursa lütfen belirtiniz.

____

____

____

Katılımınız için teşekkür ederiz.

Eposta adresi:____

20

APPENDIX C. RESEARCH PARTICIPANT CONSENT FORMS

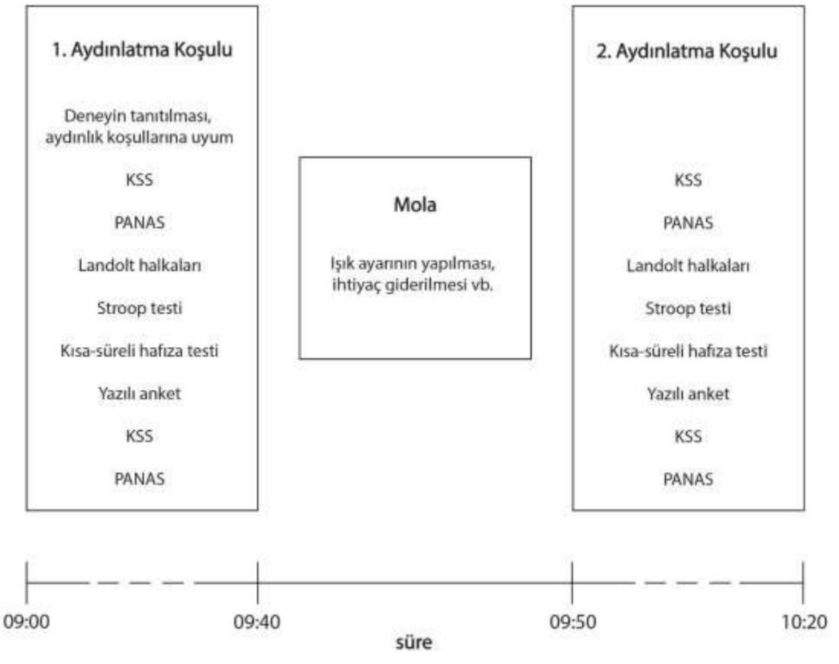
İZMİR YÜKSEK TEKNOLOJİ ENSTİTÜSÜ
SOSYAL VE BEŞERİ BİLİMLER
BİLİMSEL ARAŞTIRMA VE YAYIN ETİK KURULU

BİLGİLENDİRİLMİŞ ONAY FORMU

Sizi İzmir Yüksek Teknoloji Enstitüsü Mimarlık Fakültesi Mimarlık Bölümü öğretim üyesi Prof. Dr. Z. Tuğçe Kazanasmaz tarafından yürütülen (Tübitak 220M006 nolu 1001 projesi olan), "Ofis kullanıcılarının bilişsel/çalışma performansları, beğenileri ve duygu durumlarının en uygun pencere camı optik özellikleri ve dinamik LED aydınlatmaya göre ilişkilendirilmesi ve sınıflandırılması " başlıklı araştırmaya katılmaya davet ediyoruz. Aşağıda ayrıntılı bilgileri verilen çalışmaya katılmadan önce bu formun okunması önem taşınmaktadır. Bu araştırmaya katılmak tamamen kendi iradenizle olması koşulu esasına dayanmaktadır. Araştırmaya katılmama ya da istediğiniz zaman, hiçbir sebep göstermeden ayrılma hakkına sahipsiniz. Araştırma hakkında anlamadığınız herhangi bir konuyu çekinmeden sorun. Elde edilecek kişisel bilgiler tamamen gizli tutulacak olup, sadece çalışma kapsamında kullanılacaktır.

1. Çalışmanın Amacı
Ofislerde günışığından en etkili şekilde yararlanılması için pencere tasarımı önemini artırmaktadır. Gerek konvansiyonel pencerelerde gerekse giydirme cam cephelerde kullanılan camın doğru seçilmesi günışığının kullanıcılarda gözle görülmeyen etkileri açısından önemlidir. LED li aydınlatma sistemlerinin de benzer etkileri olmaktadır. Bu çalışma ile LED li aydınlatma ile cam seçimi birarada ele alınarak kullanıcıların beğeni, dikkat, uyanıklık durumu ve iş performansları ilişkilendirilecektir. Böylece en uygun aydınlatma koşulları tanımlanarak (aydınlatma düzeyi, renk sıcaklığı, spektral dağılım, cam türü) kullanıcıların performansı ve beğenisi yapay zeka modelleri ile tahmin edilecek (yapay sinir ağları- ANN ve bulanık mantık-fuzzy model) ve sınıflandırılacaktır.
2. Çalışmanın Süresi: 24 ay
3. Planlanan Katılımcı Sayısı: en az 200 (en fazla 300 katılımcı)
4. Araştırmada Yapılacak Genel İşler (Sorular hakkında genel bilgi, soru sayısı, ortalama cevaplama süresi)
a. Deney (performans testleri)öncesi ölçümler: Aydınlık düzeyi (lux) – yatay,iç,dış; Renk sıcaklığı (K) (masa üstü,iç,dış); SPD (iç,dış); Parıltı dağılım oranları; Aydınlık düzeyi (lux) – düşey; CS; Melatonin b. Performans(subjektif) testleri; zaman ve iş akışı . Deney tanıtıldıktan sonra 30 dakikalık ilk aşama tamamlanacak, 10 dakika ara verilecek ve katılımcının LED aydınlatma sistemini kendi istediği gibi ayarlamasından sonra ikinci 30 dakikalık aşama yapılacaktır. İkinci kısında aynı sorular tekrarlanacaktır.

İZMİR YÜKSEK TEKNOLOJİ ENSTİTÜSÜ
SOSYAL VE BEŞERİ BİLİMLER
BİLİMSEL ARAŞTIRMA VE YAYIN ETİK KURULU



Katılım Onayı:
Yukarıda yapılan açıklamaları okudum ve anladım. Araştırma hakkında yazılı ve sözlü açıklama tarafıma yapıldı, sorularımı sordum ve tatmin edici yanıtlar aldım. İstediğim zaman araştırmadan ayrılma hakkına sahip olduğum bilinci ile çalışmaya gönüllü olarak katılmayı onaylıyorum. Bu formun bir kopyası tarafıma verildi.

Katılımcının adı soyadı: ________________________ Tarih: __ /__ /_____

Katılımcının imzası: _________________

Yürütücünün adı soyadı: Prof. Dr. Z. Tuğçe KAZANASMAZ

Yürütücünün imzası: ________________

APPENDIX D. INDOOR AND OUTDOOR SPDS FOR GLASS TYPES

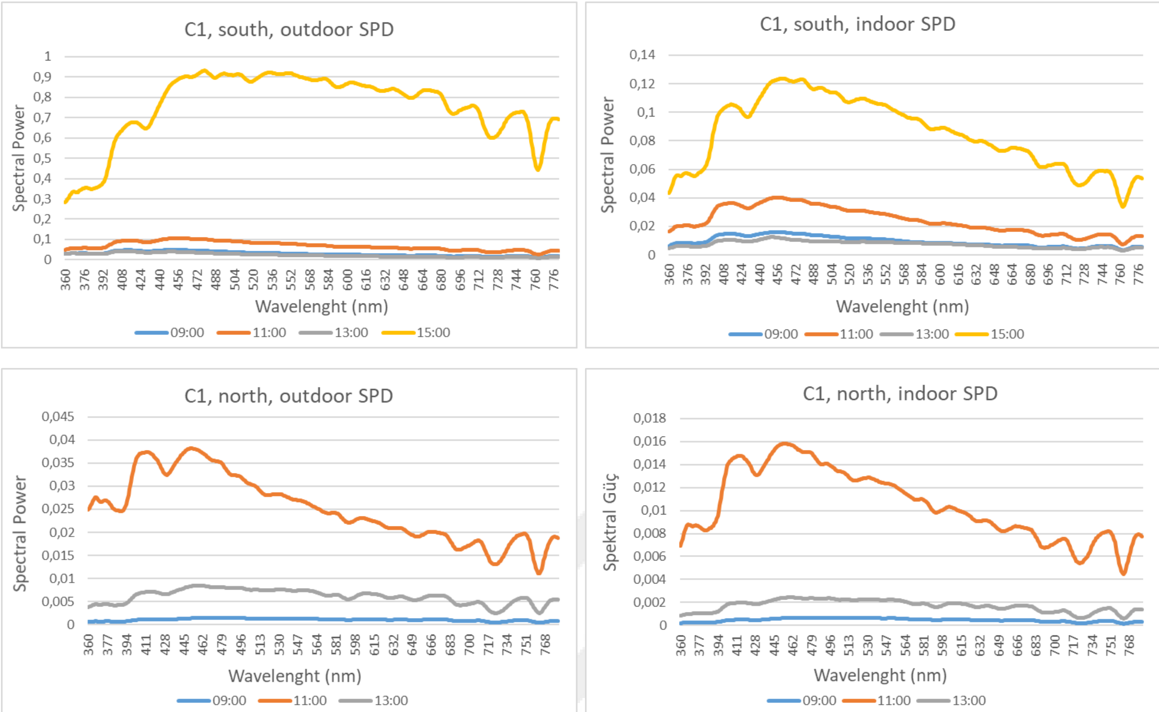


Figure D.1. Indoor and outdoor SPDs for clear, double-glazed window

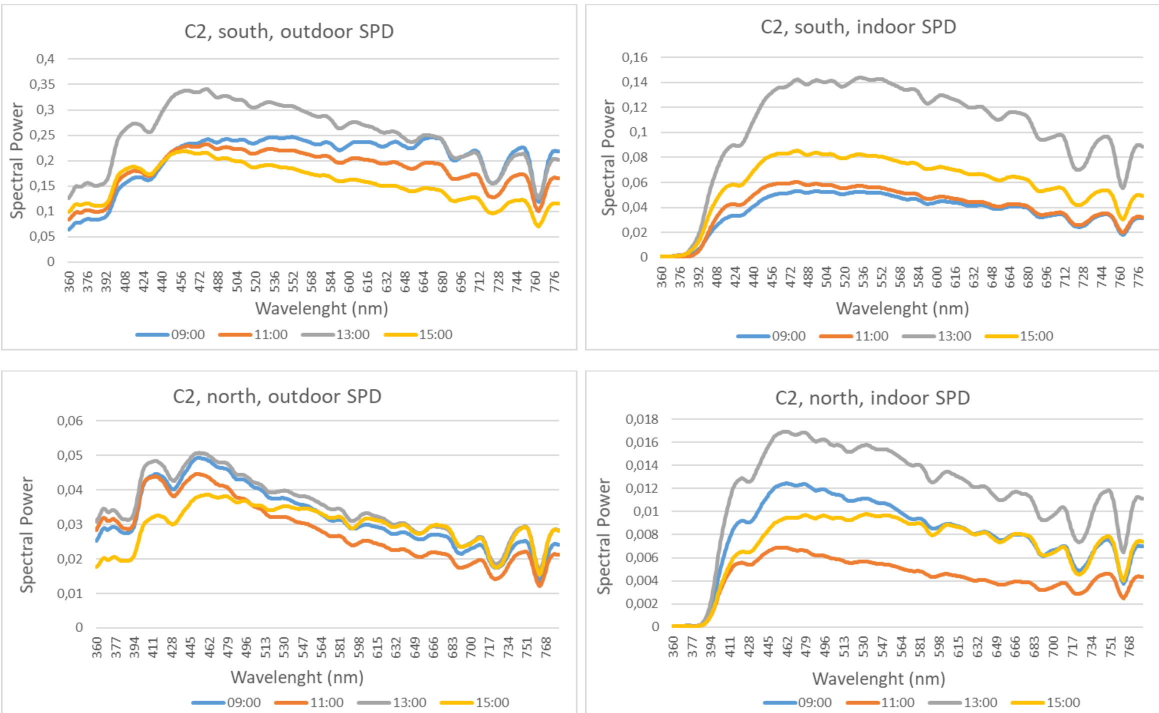


Figure D.2. Indoor and outdoor SPDs for smart glass

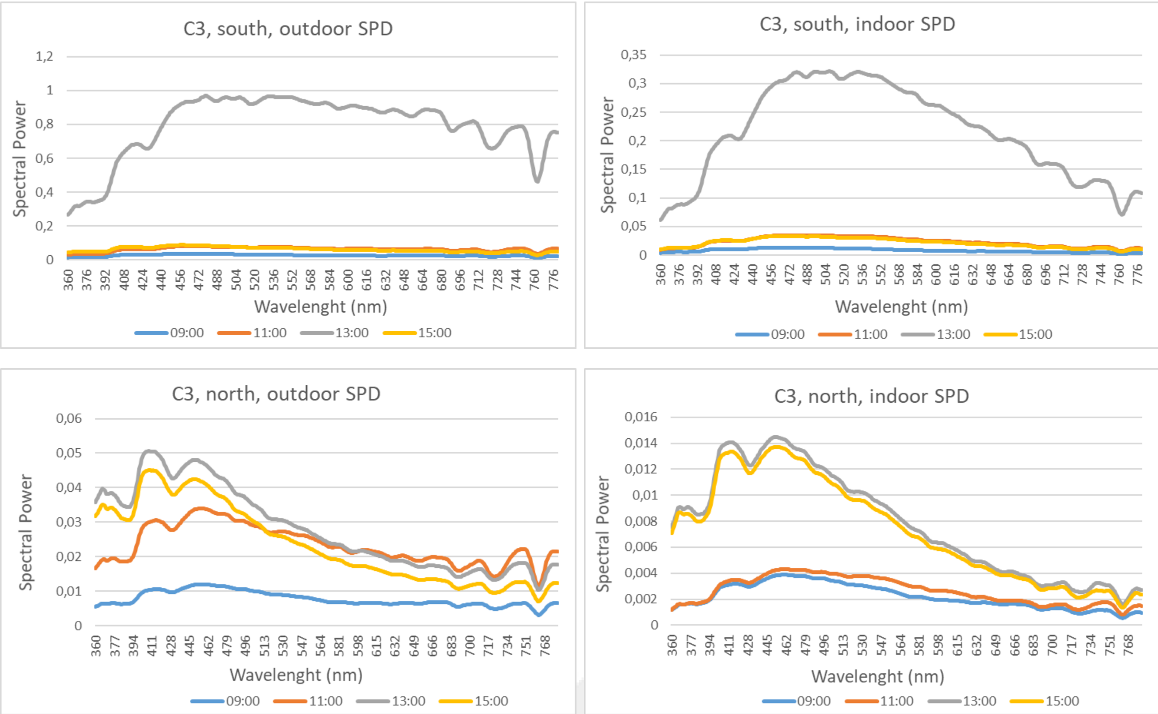


Figure D.3. Indoor and outdoor SPDs for low-e glass

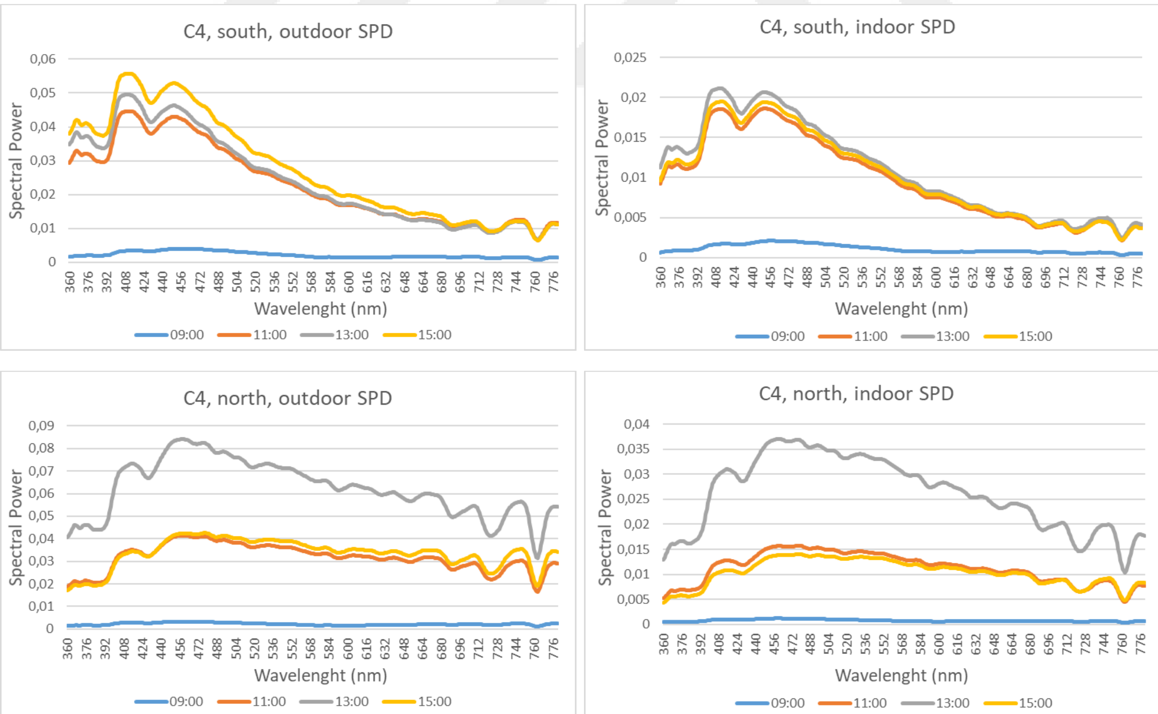


Figure D.4. Indoor and outdoor SPDs for neutral, solar low-e glass

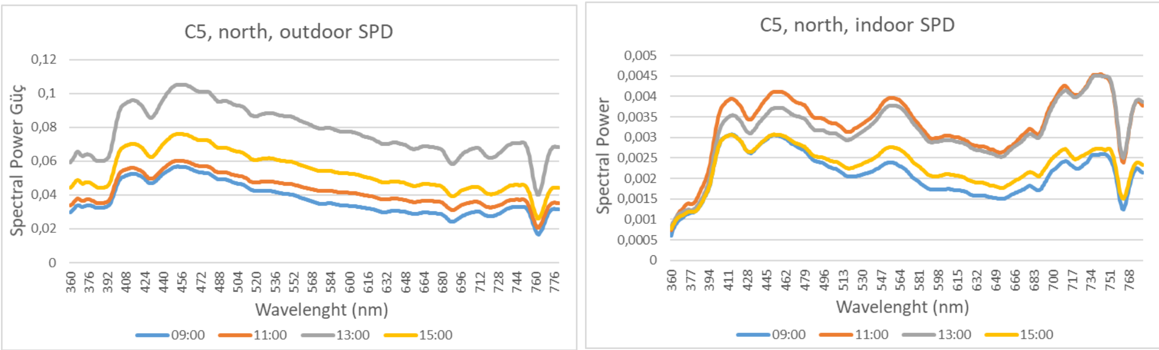


Figure D.5. Indoor and outdoor SPDs for tinted (smoked) solar low-e glass

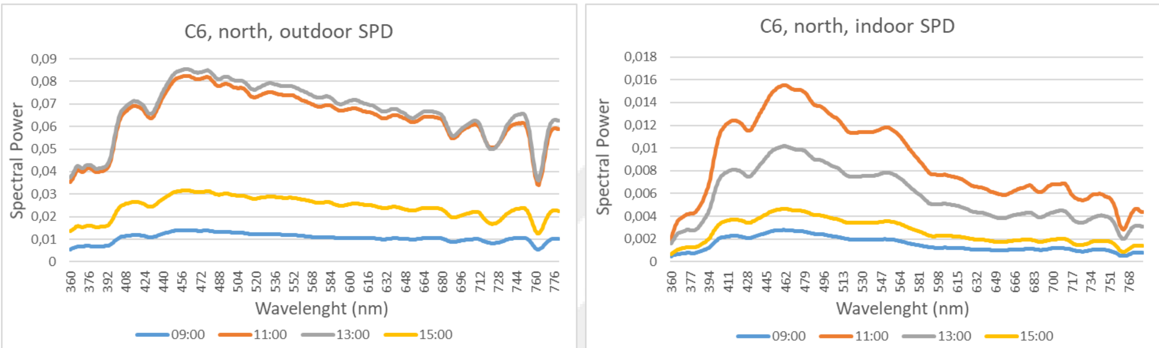


Figure D.6. Indoor and outdoor SPDs for tinted (blue) solar low-e glass

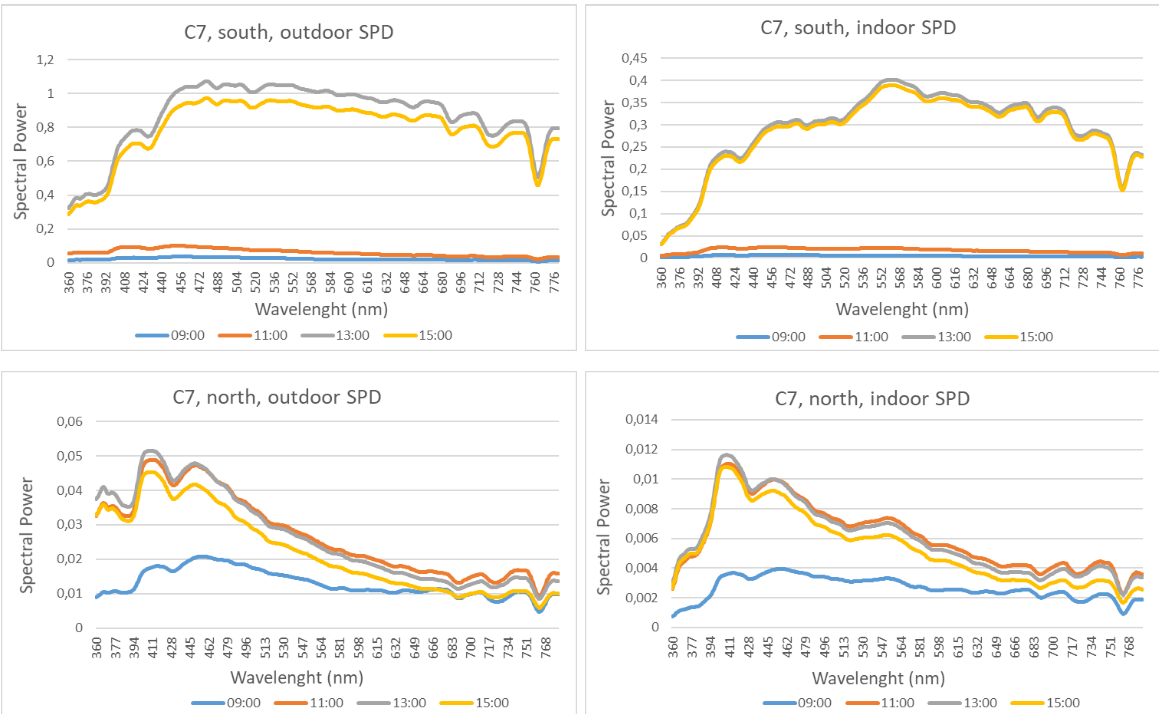


Figure D.7. Indoor and outdoor SPDs for tinted (bronze) solar low-e glass

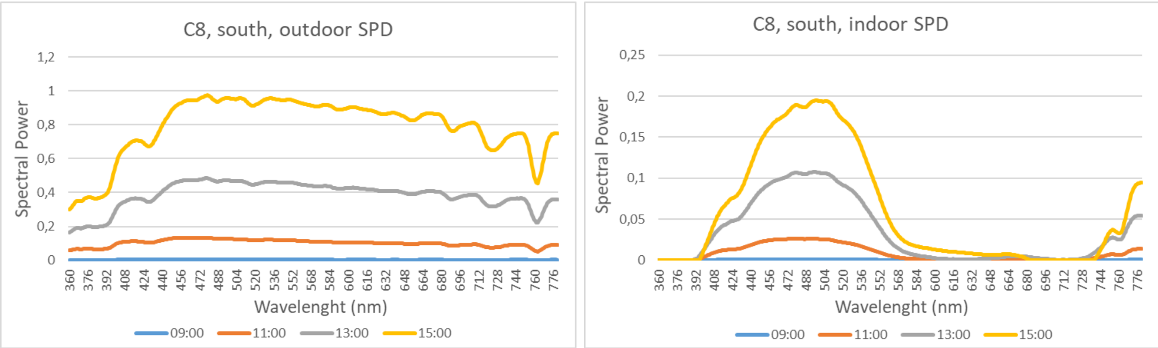


Figure D.8. Indoor and outdoor SPDs for blue (A-SI) PV glass

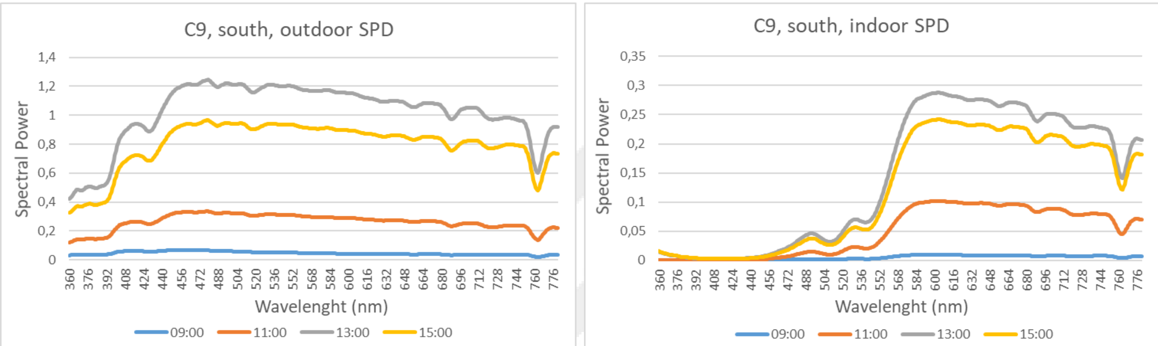


Figure D.9. Indoor and outdoor SPDs for orange (A-SI) PV glass

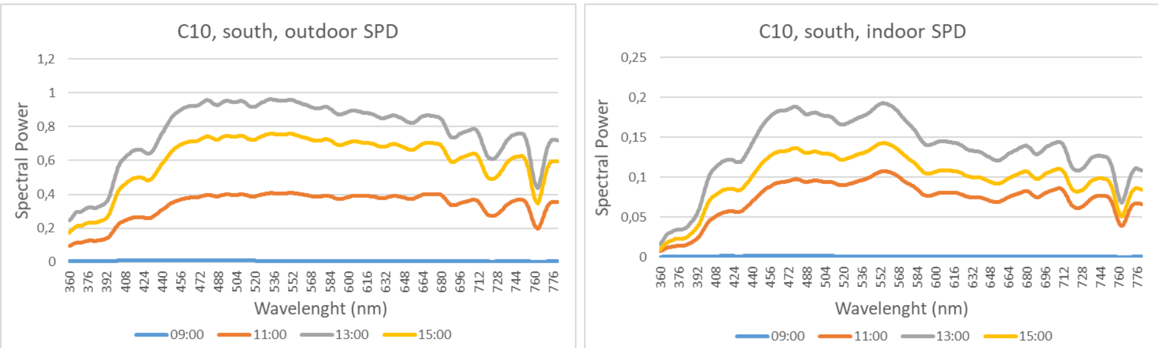


Figure D.10. Indoor and outdoor SPDs for reflective glass

VITA

Fatma Büşra KÖSE

Degree	University	Year	Title/GPA
Bachelor	Bolu Abant Izzet Baysal University	2011-2015	Architecture GPA:3.27
Master	Izmir Institute of Technology	2016-2019	Architecture GPA:3.71 *Thesis: Optimizing the Window Size and Depth of a South-Facing Room with Prismatic Panels For A Better Daylight Performance*
PhD	Izmir Institute of Technology	2019-2024	Architecture GPA:3.50 *Thesis: The Effects of Window Glazing and Dynamic LED Lighting on Daylight Quality, Occupant Alertness and Work Performance in Offices*

RESEARCH PROJECTS

220M006, Relating and Classifying Office Users' Cognitive/Work Performance, Preference and Emotions in terms of the Optimum Optical Properties of Window Glazing and Dynamic LED Lighting, Ph.D Scholar, Finalized, TÜBİTAK 1001, Project Start/End Dates: 01.04.2021-01.04.2023.

20202022, Pencere camı türlerinin iç ortam gün ışığı kalitesi, kullanıcı dikkati ve çalışma performansı üzerindeki etkileri, IYTE Scientific Research Projects (BAP), Project Researcher, Project Start/End Dates: 01.09.2020-01.09.2022.

PUBLICATIONS

Köse, F. B., and T. Kazanasmaz. 2018. "Application of a Multiple Regression Model for Estimating the Performance of a Prismatic Panel in Varying Room and Window Sizes." In *Proceedings of Beyond All Limits 2018: International Congress on Sustainability in Architecture, Planning and Design*, 17-19 October, 510-514, Ankara, Turkey.

Köse, F. B., and T. Kazanasmaz. 2019. "Prizmatik Panellerin Pencerelerde Kullanımı ile Doğal Aydınlatma Performansının Değerlendirilmesi." In *X. Ulusal Aydınlatma Sempozyumu (AYSEM)*, TMMOB Elektrik Mühendisleri Odası İzmir Şubesi, 16-19 Ekim, İzmir.

Köse, F. B., and T. Kazanasmaz. 2020. "Applicability of a Prismatic Panel to Optimize Window Size and Depth of a South-Facing Room for a Better Daylight Performance." *Light & Engineering* 28 (4).

Köse, F. B., H. E. Duran, T. Kazanasmaz, and G. Tayfur. 2022. "Office Users' Preferences on Dynamic LED Lighting and Its Impact on Arousal, Mood, and Task Performance." In *CIBSE Technical Symposium 2022: Delivering a Safe, Healthy and Sustainable Built Environment*, 21-22 April, London South Bank University, London, UK.

Köse, F. B., G. Tayfur, H. E. Duran, and Z. T. Kazanasmaz. 2022. "Lighting Quality and Work Performance Based on Glazing Types and Dynamic LED Lighting." In *2021 Joint Conference-11th International Conference on Energy Efficiency in Domestic Appliances and Lighting & 17th International Symposium on the Science and Technology of Lighting (EEDAL/LS: 17)*, 1-6. IEEE, 1st-3rd June, Toulouse, France.

Kazanasmaz, T., F. B. Köse, H. E. Duran, and G. Tayfur. 2022. "Human-Centric Lighting: Variations in CS, EML, and SPDs Based on Glazing and LED Lighting Technology in an Office." In *1456th International Conference on Recent Innovations in Engineering and Technology*, 9-10 December, Athens, Greece.

Kazanasmaz, Z. T., F. B. Köse, and G. Tayfur. 2023. "Emerging Concept of Human-Centric Lighting in Literature Review." In *2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, 1-6. IEEE, 6-9 June, Madrid, Spain.

Kazanasmaz, T., F. B. Köse, H. E. Duran, and G. Tayfur. 2023. "Ofis Kullanıcılarının Bilişsel/Çalışma Performansları, Beğenileri ve Duygu Durumlarının En Uygun Pencere Camı Optik Özellikleri ve Dinamik LED Aydınlatmaya Göre İlişkilendirilmesi ve Sınıflandırılması." In *XI. Ulusal Aydınlatma Sempozyumu (AYSEM)*, TMMOB Elektrik Mühendisleri Odası İzmir Şubesi, 2 Kasım, İzmir.