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Mindful Lighting-
Exploring the visual and non-visual comfort of residential lighting to support the restorative space through environmental psychology and neurosensory perspectives.

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Abstract:

This research investigates the influence of lighting on emotional well-being and relaxation in home environments, addressing the increasing disconnect between modern lifestyles and natural circadian rhythms. The study explores how light intensity, and the directionality of light (direct/indirect) affect physiological and psychological responses. Adopting a mixed-methods approach, the research combined physiological data from electroencephalography (EEG) with psychological data from self-report questionnaires (Affect Grid and Activation-Deactivation Adjective Check List - AD ACL) and semi-structured interviews. Twenty participants were exposed to four controlled lighting scenarios: Direct High intensity (DH), Direct Low intensity (DL), Indirect High intensity (IDH), and Indirect Low intensity (IDL).

The findings indicate a notable divergence between physiological and psychological measures. EEG data, analyzed for arousal and valence, did not reveal statistically significant differences across the four lighting conditions. Conversely, subjective measures showed significant impacts. The AD ACL scores demonstrated that lighting conditions significantly influenced participants' feelings of calmness ($p=0.0003$) and energy ($p=0.0001$). Low-intensity lighting was associated with higher calmness and lower energy scores, while high-intensity scenarios correlated with increased energy. Affect Grid data and interview responses further indicated a strong preference for indirect, low-intensity lighting (IDL), which was consistently described as the most "cozy," "relaxing," and "pleasant," contributing to a restorative environment. Direct, high-intensity light (DH) was generally perceived negatively.

In conclusion, while psychological responses strongly supported the hypothesis that low-intensity and indirect lighting enhance emotional well-being and create a restorative atmosphere, the corresponding physiological changes in EEG-measured arousal and valence were not statistically confirmed with the current methodology. The study underscores the significant impact of light intensity and direction on subjective emotional states and highlights the value of a mixed-methods approach in understanding the complex relationship between lighting, human perception, and well-being in residential settings.

Master Thesis:
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Magnus Pedersen Gram

Supervisors: Georgios Triantafyllidis, Morteza Hosseini

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Abstract

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1.Introduction

1.1. Background

The evolution of technology has changed the world in terms of how professional and personal life is spent. The amount of time spent indoors and on screen-based activities has increased, which allows cognitive and sensory stimulation to significantly occupy our everyday life. Digital technologies connect people in social and informative ways but also cause work and the expectation of staying informed to be part of an environment where the boundaries between professional and personal life are becoming indistinct.

This information age is causing rising demands from both professional and social responsibilities, forming an environment where stress and mental fatigue are frequently experienced in modern society. The transition between daily chores and slow-paced activities before bedtime is a crucial time for mental restoration. During the evening hours, melatonin in the human body—a hormone that serves as a cue for the biological clock and supports sleep for the brain—should not be suppressed by any sort of stimulation, such as higher light levels (Zisapel, 2018).

However, most of the living patterns in modern society contradict the natural transition, without the aligned daily routines with the biological clock, the circadian rhythm would have consequences beyond momentary discomfort and potentially impact the restore quality for the brain, long-term stress levels, and overall well-being. (Houser and Esposito, 2021a).

There are several factors that influence the ability of people to relax and feel at ease. For example, the noise level, visual comfort, and air quality is known to affect how we feel in a space (Al horr *et al.*, 2016). Lighting is a big contributor in terms of visual appreciation, sense of direction, and how we perceive the environment. Nevertheless, it has an evident influence on non-visual aspects, including physiological effects and the circadian rhythm. With the problem and potential addressed above, the questions for this research in the current situation concern how lighting can align the modern way of living physiologically and psychologically. Does lighting influence the human brain and emotions and can it enhance emotional comfort and reduce stress in a home environment.

According to the initial questions, literature reviews were collected and investigated. The findings and solutions gave an overview of the research previously done and potentially identify the research gaps. Most of the research examines institutional lighting for productivity and commercial purposes. Compared to research on lighting in residential environments, less attention has been focused on the valid method and evidence on creating restorative home environments, especially regarding how and what lighting can benefit people in private homes (Osibona, Solomon and Fecht, 2021; Guo, Qi and Hu, 2023).

In terms of the health factors in the mental system, there is a more extensive amount of research about how artificial lighting, in general, influences the circadian clock. It is well established by research that the light spectrum or correlated color temperature of the light (CCT) has a significant influence on melatonin, which can directly reduce sleep duration and lead to sleep disorders (Guo, Qi and Hu, 2023).

The primary aim of this research is to develop evidence-based yet accessible guidelines that enable individuals to implement beneficial lighting modifications in their homes without requiring specialized knowledge or bigger investments.

By identifying and testing specific lighting parameters including intensity, color temperature and distribution that support and restorative environment, the connection between scientific understanding and practical application would create a basis for simple guidelines for consumers, which would be in the form of a White Paper document.

As the development of urbanization continues and the working pattern evolves, an intentionally designed restorative environment becomes more influential than before. By supporting individuals to optimize their existing surroundings, it could contribute to more sustainable approaches to human well-being adapting to the modern way of living and routines.

1.2 Research question and hypothesis

Based on the literature review, there is a gap concerning the physiological and psychological response in the context of relaxation and human well-being in a home environment. Based on the literature review, 18 keywords were extracted, which were used to gather further literature to get a comprehensive investigation of how lighting characteristics influence mood and well-being. As shown in Figure 1 Literature Review, there were 8 papers collected from the literature research.

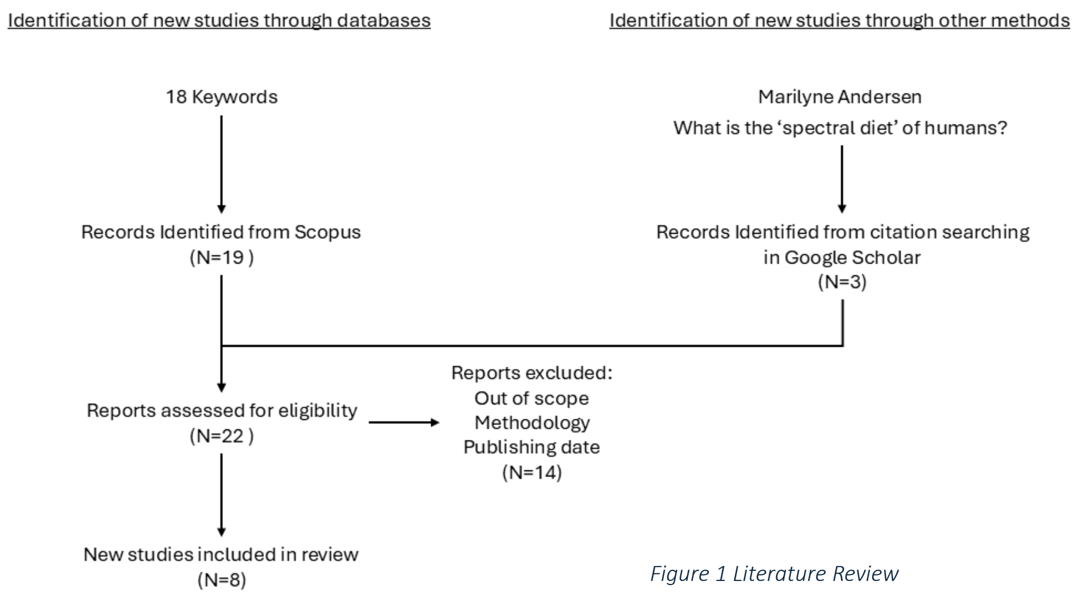


Figure 1 Literature Review

Based on the collected papers, different light parameters and methodologies were identified that created a foundation for the methodology used in this paper. The different parameters were classified and compared to determine which ones should be further tested and which should be determined by literature. Brightness or intensity of the light is one of the dominant parameters that influence the ability to relax and influence mood. (Webler *et al.*, 2019a; Houser *et al.*, 2020; Houser and Esposito, 2021a; Fu *et al.*, 2023; Siraji *et al.*, 2023)

The distribution and the placements of the fixtures also have a big influence on how the light is perceived and the visual comfort. These were also important parameters that were a common subject in most of the papers. (Webler *et al.*, 2019b; Houser *et al.*, 2020; Aslano˘ Glu *et al.*, 2021; Houser and Esposito, 2021a)

In addition to the intensity and the distribution of the light are parameters like correlated color temperature (CCT) duration and color rendering index (CRI) are also important factors. Figure 2 provide an overview of literature and the methodology and light parameters each of the papers contained.

NAME OF PAPER	Summary	Methodology	Light Parameters
What is the 'spectral diet' of humans? (Webler, Forrest S et al. 2019)	This paper explored the visual and non-visual effects of light on human physiology and behavior.	Comparative Analysis ▲ Site test using image calculation	★ Intensity Duration Wavelength Timing ● illumination patterns
Light exposure behaviors predict mood, memory and sleep quality (Siraji, Mushfiqul Anwar et al. 2023)		⬟ online survey	★ Intensity Light exposure behaviors Quantity of blue light
The non-visual effects of correlated color temperature on the alertness, cognition, and mood of fatigued individuals during the afternoon (Chen, Quan et al. 2024)	A study for people who work with long hours focus like railway dispatchers, using EEG to test the correlation in metal fatigue, alertness, mood change under the environments with different CCT.	Site test ▲ EEG	CCT
Human-centric lighting: Myth, magic or metaphor? (Houser, K et al. 2020)	This paper discussed visual and non-visual response, Circadian, neuroendocrine and neuro behavior are important for human health and should be considered on-par with visual responses.	Literature review ⬟ Comparative Analysis	★ Luminance ● Distribution light spectrum Spectral power ★ Light level ● Spatial patterns
Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process (Houser, K.W. & Esposito, T. 2021)	Guideline to consider in the process of designing lighting to suit the wellbeing and circadian rhythm.	Integrated principles of HCI, standards and design process.	Temporal pattern Spectrum ★ Intensity Duration
The Effect of Correlated Color Temperature and Illumination Level of LED Lighting on Visual Comfort during Sustained Attention Activities (Fu, Xiaoyun et al. 2023)	The paper tested if there is a correlation between the influence of CCT and illuminance level in LED lighting parameters on human visual comfort.	▲ EEG Sustained attention test (SART) Evaluation scale	CCT ★ Illuminance level
Short-term analysis of residential lighting: A pilot study (Aslanoğlu, R et al. 2021)	The study aimed to collect data and conduct a short-term analysis about several interconnected factors related to residential lighting.	⬟ Online survey	Duration Quantity ● Uniformity ★ Perceived brightness level CRI ● Shadow patterns
Role of architectural design in creating circadian-effective interior settings (Alkhatatbeh, B. J., & Asadi, S. 2021)	Analyze the architectural factors within the daylight and artificial light, contributed to circadian-effective lighting, design parameters for non-visual comforts.	Literature review ⬟ Analysis	● Indirect/ direct luminaire Distribution

Figure 2 Literature parameters

On background on the literature and the research review the final Research question and hypothesis were formed. From Figure 2 both the intensity of the light highlighted with a "star" and the distribution highlighted with an orange "circle" were two key factors across the research papers, both are two parameters that are easy to test and control in a testing environment.

1.2.1. Research Question

How does <u>intensity</u> and <u>luminance from direct/ indirect light sources</u> influence the physiological, psychological response in the context of relaxation and enhances emotional well-being in home environment.

1.2.2. Hypothesis 1

Low <u>intensity</u> in the space would keep the arousal low, increase the positive valence and support the restorative environment.

1.2.3 Hypothesis 2

The <u>luminance from Indirect light</u> in the space would keep the arousal low, increase the positive valence and support the restorative environment.

1.2.4. Approach

The methodology used in the collected papers was a combination of quantitative and qualitative methodologies. Several papers used quantitative methods to measure the responses to several different light parameters. Site tests incorporating specific measurements like image calculation, standardized performance evaluations, Positive and Negative Affect Schedule (PANAS) and Electroencephalography (EEG), are frequently employed in several of the papers, indicated by the green “triangles” in Figure 2 (Webler *et al.*, 2019b; Fu *et al.*, 2023; Li *et al.*, 2024). These methods provide quantitative data on physiological changes and light effects on alertness, fatigue, visual comfort, and behavior.

Literature with qualitative methodologies highlighted with a purple “pentagon” gives a deeper understanding and causes to the different results. Moreover, the literature reviews and comparative analyses are essential to understand existing knowledge and help to understand subjective experiences and practical design considerations (Houser *et al.*, 2020; Alkhatatbeh and Asadi, 2021a; Aslanoˇ Glu *et al.*, 2021; Houser and Esposito, 2021a; Siraji *et al.*, 2023).

Using both quantitative and qualitative methodologies will support a comprehensive viewpoint on physiological and psychological responses in lighting. From the physiological perspective, the utilization of EEG gives an evident biological signal, which encourages a scientific interpretation for the light effects on brain. Subsequently, the qualitative methodology like semi-constructive Interviews or the emotional Likert lists would help to reveal the insights psychologically, creating the coherent connection to the physiological response. As a result, it would create a broadened understanding of wellbeing through an unfold in how individuals respond and be affected to different light conditions.

2. Theoretical Framework

2.1. EEG

Electroencephalogram (EEG) is a method to measure the electrical activity in the brain. The brain cells communicate electrical impulses that make the body work. EEG is a non-invasive way to get readings from the brain, which consists of metal or electrically conductive discs that are placed on the scalp, named electrodes. These electrodes detect the small electrical changes produced by the brain neurons as they communicate. The activity can be recorded, amplified and visualized as waveforms on a screen giving a picture of electronical pattern in the brain. These waveforms are characterised by the frequencies measured in Hertz (Hz). The common frequencies are:

Delta is in the range of 0.5-4.0 Hz. It's dominant during sleep when also called REM-Sleep. It is associated with unconsciousness.

Theta is in the range of 4.0-7.0 Hz. It is more dominant during light sleep and deep relaxation or mediation. It is also associated with memory processing.

Alpha is in the range of 8.0-12.0 Hz. Is prominent when a person is in a relaxed awake state. It is associated with calmness and being in a relaxed state.

Beta is in the range of 13.0-30.0 Hz. Is active during active thinking and concentration. It is associated with stress and active processing of information.

Gamma is in the range of 30.0-100.0 Hz and above. Gamma waves are active during high level cognitive processing.

(Roohi-Azizi *et al.*, 2017)

Beside the frequency itself, there is also the power of the frequencies that need to be noted. The frequencies are how quick the signal waves are turning, while the power is how high the peak of each wave is, also called amplitude. Therefore, the power is recorded over all the electrodes, and it is called Band power in the realm of EEG, and it gives an indication on which frequency are the dominant one in that moment. (Saby and Marshall, 2012)

2.1.1. 10/10 System

The EEG 10/10 system is a standardized method for placing electrodes on the scalp for electroencephalography (EEG) recording. The "10/10" refers to the distances between the electrodes, which are positioned at 10% intervals along the scalp. This system typically involves 64 standard positions but can also expand up to 81 in total, offering a higher resolution compared to the 10/20 system, which has only around 21 placements.

Electrode placement in the 10/10 system may vary dependently on the type of EEG being performed and the specific EEG headset in use. This standardized approach ensures consistent and reproduceable electrode positioning across different individuals and recording sessions.

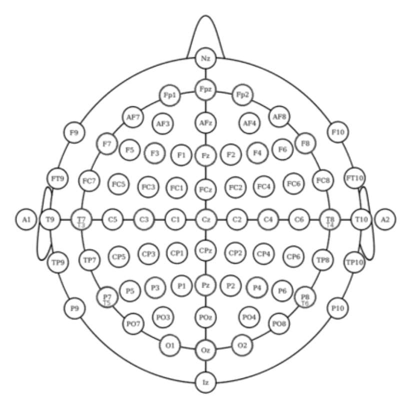


*Figure 3 EEG 10-10 System (*EEG Electrode Positions (10-20 vs. 10-10 System)*, 2025)*

Each electrode position is labeled based on the underlying brain region. For example, letters such as “F” for frontal and “C” for central are combined with numbers. These numbers correspond to the hemisphere of the brain: odd numbers represent the left hemisphere, even numbers the right, and the letter 'z' designates as the middle line. For instance, F3 refers to the left frontal region, while Cz is located at the central line see Figure 3 for reference.

The 10/10 system enables high-resolution EEG data collection across various brain regions and is widely used in both research and clinical settings (*EEG Electrode Positions (10-20 vs. 10-10 System)*, 2025).

The brain is divided into two hemispheres, the right and left hemisphere, each one has four lobes. Each lobe is divided into the frontal, temporal, parietal, and occipital lobe that has distinct functions:

- **Frontal lobe**: Involved in personality, emotion, judgment, movement, and intelligence.
- **Parietal lobe**: Processes sensations such as touch and pain, and contributes to spatial and visual perception, as well as interpretation of vision, hearing, and memory.
- **Occipital lobe**: Responsible for interpreting visual information such as color, light, and movement.
- **Temporal lobe**: Plays a key role in memory, hearing, and language comprehension.

(*Brain Anatomy | Mayfield Brain & Spine Cincinnati, Ohio*, 2018)

Understanding the functions of these lobes is crucial when it comes to the electrodes positioning. An accurate placement over the relevant brain regions ensures that the EEG captures the appropriate neural activity for the intended diagnostic or research purpose.

2.1.2 Valence and Arousal model

The Valence and Arousal model, also known as the circumplex model of affect, is a two-dimensional way to categorize different emotions. It is widely used in psychiatric and neuroscience research where Valence ranges from unpleasant to pleasant, and Arousal ranges from tense/excited to tired/calm, see Figure 4. One primary advantage of using the valence and arousal model is in its flexibility and broad applicability. It supports both quantitative and qualitative analyses, allowing different types of tests to map emotional responses while maintaining interpretability across diverse methodological approaches. (Posner, Russell and Peterson, 2005)

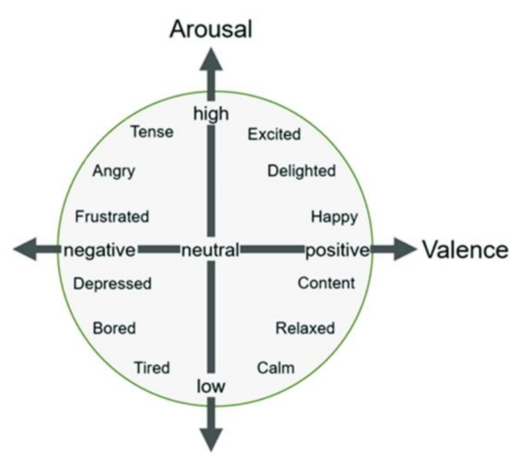


Figure 4 Russell’s Valence Arousal model (Posner, Russell and Peterson, 2005)

2.1.3. Arousal Calculation

The calculation method for Arousal relies on the ratio between Beta and Alpha brainwave activity. Beta waves are typically linked to the alertness, activity, and attention, whereas Alpha waves are associated with the states of relaxation or meditation. If Beta activity predominates over Alpha activity, the resulting Arousal score will be higher. Within the model, a higher score corresponding to the states characterized as 'tense' or 'excited'. In the opposite condition, where Alpha activity is stronger than Beta activity, the Arousal score becomes lower, corresponding to the states described as 'tired' or 'calm' in the model. The equivalence point of this equation is “1”, where both alpha and beta is the same. For further reference in the rest of this study, this equation is marked as Arousal (A) (Kislov *et al.*, 2023; Fang *et al.*, 2025).

$$Arousal\ (A) = \frac{Beat}{Alpha}$$

Another type of arousal calculation is based on the higher Beta Low and Gamma levels (indicators of alertness and cognitive activity) increase arousal, while higher Alpha levels (associated with calmness) reduce arousal (Garg *et al.*, 2022). In this calculation, the equivalence point would be “0” if the result is negative, then the Alpha power is more dominant, which indicating a more relaxed and calm state. For further reference in the rest of this study, this equation is marked as Arousal (B).

$$Arousal\ (B) = (Beta\ Low\ Average + Gamma\ Average) - Alpha\ Average$$

2.1.4. Valence Calculation

The method to calculate valence is based on frontal alpha asymmetry that compares the Alpha power on the right and left side of the brain (Davidson, 1992; Zhao, Zhang and Ge, 2018).

By adding and subtracting the alpha right and left, it normalizes the difference between their sums. This calculation has the equivalence point at “1”. For further reference in the rest of this study, this equation is marked as Valence (A) (Poole and Gable, 2014; Metzen *et al.*, 2021).

$$Valence\ (A) = \frac{Alpha_{Right} - Alpha_{Left}}{Alpha_{Right} + Alpha_{Left}}$$

In addition to the previous Valence calculation, there is another method without normalising the difference. This simplified method compares the left hemisphere to the right hemisphere of the brain, which is the opposite direction from Valence (A). For further reference in the rest of this study, this equation is marked as Valence (B). In this calculation, the equivalence point would be “0” if the result is negative, then the Alpha F4, which is the right side of the brain is more dominant compared to Alpha F3, the left side of the brain. (Poole and Gable, 2014; Metzen *et al.*, 2021)

$$Valence\ (B) = Alpha\ f3 - Alpha\ f4$$

2.2. Light Parameters

2.2.1. Visual Element of Light

2.2.1.1. Luminance

The six visual principles of light within the architectural space have been introduced to provide the design parameters considered to create a desired spatial experience, which includes illuminance, luminance, colour and temperature, height, density, direction and distribution. (Descottes and Ramos, 2013) Among the six principles, luminance plays a crucial role in how the light interacts with space and perceived by the human eye and brain. Luminance and brightness are normally measured in candela per square meter. The visual property of luminance determines the quantity and intensity of emitted light from the surface, and the ratio of luminance would be used to differentiate between objects or spaces, giving the rhythm or the orientation across pathways without the visual fatigue. It also mentioned the emotional influence from the indirect light, the luminated surface or object itself as the reflected light source, in the religious architectural space.

The size of luminous surface under a high level of luminance is crucial to determine the light as a glare or a sparkle. “Glare is both a function of luminance area and of the lighting position within a field of view.” (Descottes and Ramos, 2013) It gives the different interpretational factor for us that the placement and the types of light source within the point of view could create visual comfort and transform the atmosphere of a space.

2.2.1.2. Direction and Distribution

“The direction and distribution of light has the capacity to accentuate or negate the presence of objects and form,” which explains their determined characteristics of shaping the space with different possibilities. The directionality of light can be categorized in three: up, down or multidirectional, and the application on surface as direct or indirect. The distribution of light can be generally divided into focused or diffuse light (Descottes and Ramos, 2013). With different combinations of the light, it would change the impression of the space and give people different emotions. For example, the indirect diffuse upplight would draw our attention to the end limit of the upper space, giving the ambient atmosphere and broaden the sense of building structure; the direct diffuse downlight would illuminate a certain area of floor, giving the prominent luminous surface and grounding the visitors in the space with a sense of stability.

Within lighting design for stage production, the narrow concentrated light beams often used to create the visual threshold to diverge the everyday world and the theatrical realm to entered. While the diffuse and ever-changing orientation of the daylight has the ability to form the outlines of architecture and accentuate the textures through seaming the experience and space. Moreover, there is also the discussion of the rising trend of architecture into the age of transparency and equality. With the multi-dimensional, evenly distributed light source, all the objects in the space are rendered equally visible, which strengthens the idea that light and architecture becoming one and the same.

2.2.1.3. The Appreciation of Light

People resonate the lighting with their own preferences and background experiences in life. In the article “Lighting as an Integral Part of Architecture” in the journal from Richard Kelly (Kelly, 1952), a proposed perspective of visual perceptions that breaks light into three experiential elements: focal glow, ambient luminescence, and play of brilliants.

Focal glow is associated with the pool of light at your favorite reading chair. It draws attention and highlights the main character from the surroundings. Ambient luminescence is described as the twilight haze on a wide river where shore and water and sky are indistinguishable. It renders objects evenly with shadowless illumination and suggests a sense of reassuring and restfulness. Play of brilliants is the trees outside the window interlaced with the beams of spotlights or the sunlight leaking through leaves which also has its own words in Japanese, Komorebi.

The interplay and balance among these three elements, each contributing uniquely to the visual and emotional experience of a space, assign the layers of light in the space. It was recognized that no single element is sufficient on its own. Focal glow without ambient luminescence can feel harsh or isolating. Ambient light without focal points becomes monotonous and disorienting. Too much brilliance without grounding leads to sense of distraction. The triad relationship of lights offers not just technical number in science, but a way of seeing and feeling, where light becomes a tool of both function and poetry. "Variety is the spice of light" is to utilize the three elements for visual sensation and bring out the designated value in space. (Kelly, 1952)

2.2.1.4. Light Parameters and Visual and Non-visual Effect

Light has an influence on humans visually, biologically and behaviorally, that is because our body, brain and emotions can have visual and non-visual, immediate or prolonged responses from light exposure.(Houser *et al.*, 2020) The above considerations lead to the rise of human-centric lighting design within the architectural and design field.

A systematic lighting design method for the built environment according to the Human-centric lighting realm has been discussed and introduced, which considered the light variables, each of them contributes to the way we perceive architecture, navigate spaces, and support people psychologically and physiologically through the coordination of both visual and emotional quality of the environment. The four light variables are: light spectrum, how the light render the color of things; light level, the quantity of light in radiometric and photometric units; spatial patterns, the luminance distribution of the three-dimensional space; temporal patterns, the timing and the duration of exposure (Houser *et al.*, 2020). It introduced the possible solution for visual comfort based on the above variables, such as moving an extremely bright light source to a different viewpoint of people, reducing the luminance of light source, or changing the source spectrum. Similar light parameters were addressed in another review paper, it was aimed to research the characteristics of light influenced by architectural factors and further giving the impact on circadian effectiveness. It linked the affected light parameters to indoor lighting spectrum, quantity, spatial pattern and temporal pattern (Alkhatatbeh and Asadi, 2021b). Among them, the intensity, spectrum and spatial pattern were affected by the architectural factors such as the reflectance of interior surfaces or furniture's, color and geometrical properties in space. The luminous environment generates the retinal image which provides information to enable the visual perception process to recognize the objects and surfaces that form the visual clue from perceived environment. Thus, the dependable variants of the intensity and spatial pattern have been discussed. The impact of light distribution on the perception of the spaciousness of an interior is much less stable than the perception of brightness because spaciousness is associated with factors other than the luminous environment, such as the amount and arrangement of furniture in space (Boyce, 2014). Among all, spatial pattern and light level have the probability to adapt the existing environments and include the individual differences, which may be more applicable in different spaces with limited choices of light source.

The human visual system is composed of a variety of neural mechanisms which allows us to see space, details, color and motions in the world (Webler *et al.*, 2019b). It explains the inherently intertwined psychophysical and physiological responses from light, which has also been systematically constructed into the overview graph (see Figure 5) in relationship between light and human responses (Houser and Esposito, 2021b). It gave the framework and considerations for designing the light for different types of individuals like day-active person, the operational goals such as safety or relaxed atmosphere, lighting controls including intensity and spectrum, and spatial interventions like temporary visual barriers.

With the above discussion about the interaction of light parameters, it has the potential in the light quantity as to considered non-visual influence received from light, and spatial distribution of light in the three-dimensional field within the indoor spaces.

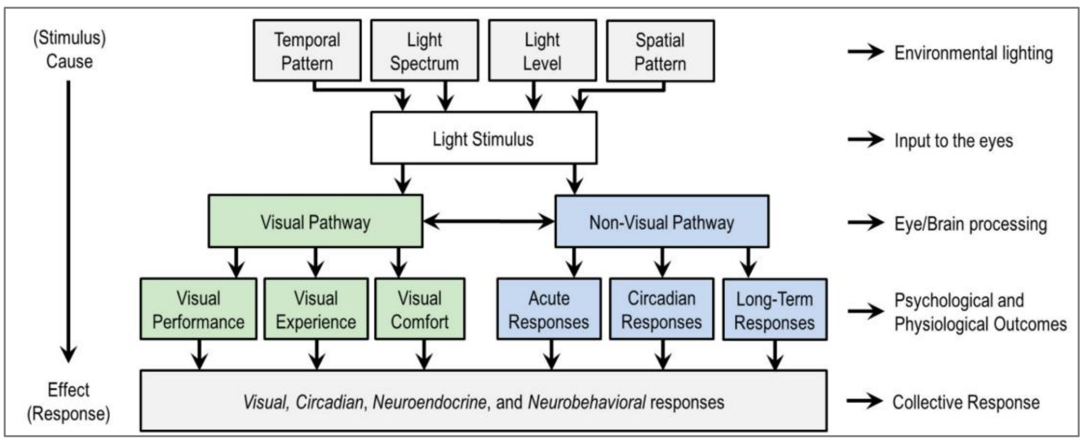


Figure 5 The overview of light and human responses. (Houser and Esposito, 2021b)

2.2.2. Direct and Indirect Lighting

The directionality of the light plays a crucial role in how we perceive space. Both direct and indirect lighting serve different purposes and contributes to form a space with specific atmospheres and functionality. Direct lighting, also referred to as focal glow in Richard Kellys journal, emits directly onto a specific area or object. The light source is typically visible to the observer. Common types of direct lighting include desk lamps, pendant lights and spotlights. These lighting solutions are often used as task lights due to their generally stronger and more focused illumination. However, if the intensity gets too high can it create strong contrasts and glare, potentially causing visual discomfort.

Indirect lighting is the reflected light from a surfaces like walls, ceilings and furniture. This reflective luminance creates a softer and more diffuse light that enhances ambience and reduces the likelihood of glare. Common applications of indirect lighting in architectural spaces include uplighting and wall washing. Studies have shown that a combination of Indirect and direct lighting creates a calmer and more pleasant environment compared to only direct lighting. Indirect lighting also contributes to a greater perception of spaciousness. (Shin *et al.*, 2015). Furthermore, the physiological effects of lighting on occupants have also been discussed. Direct luminance, which comes straight from the light source to the eyes, supports visibility and energy efficiency but can also lead to discomfort. In contrast, indirect illuminance involves light that has undergone at least one reflection before reaching the eyes. This type is preferred for minimizing visual discomfort and enhancing non-visual effects, such as mood and circadian rhythm regulation. (Alkhatatbeh and Asadi, 2021b)

2.2.3. Intensity

Light intensity, also referred to as light level, is one of the most influential parameters in architectural design within spatial context. It often directly influences our ability to perform tasks, perceive contrast, and arouse emotional memory from our surroundings. Higher light levels can stimulate alertness and support activities that require focused attention, while lower levels can support relaxation or create a sense of intimacy. In spatial context, the composition of intensity can also define zones, emphasize depth, and support the layering of visual experiences across a room or structure (Alkhatatbeh and Asadi, 2021b). Beyond its functional and perceptual effects, light intensity has a profound impact on the human biological clock, mood, and cognitive performance. The circadian rhythm, which regulates sleep-wake cycles, is heavily influenced by the daily patterns of light exposure.

Darkness stimulates the production of melatonin and other hormones essential for rest and recovery. During morning and daytime hours, exposure to higher light intensity, especially the light embodied with blue wavelengths found in natural sunlight, is beneficial for the synchronization of the internal clock. The light exposure signals the brain to suppress melatonin, thereby increasing alertness and enhance energy levels. In contrast, during the evening, reduced light levels in natural settings signal the body to transition into rest mode, promoting melatonin production and preparing for sleep.

However, exposure to artificial light with high intensity and blue wavelengths during evening hours can interfere with this natural process. This disruption can lead to difficulties falling asleep, fragmented sleeping patterns, and a general desynchronization of our internal clock, impacting overall health, daytime vitality, and well-being. (Webler *et al.*, 2019b; Houser *et al.*, 2020; Aslano˘ Glu *et al.*, 2021; Houser and Esposito, 2021a)

2.2.4. CCT

Correlated colour temperature (CCT) refers to the perceived colour of light, which significantly affects the human body through both visual and non-visual pathways. Colour temperature of light influence how we perceive the colour, surfaces and the environment. Regarding the non-visual effect, a higher CCT such as 12000K that is over the normal for daylight is increasing alertness and attention compared to lower CCT under 6500K (Li *et al.*, 2024).

2700K is one of the wildly used as a warm white colour tone in modern LED light bulbs. This setting support daytime circadian stimulation when the intensity is dimmed up, it contributes to circadian protection during nighttime with a lower intensity (Ticleanu, 2021).

Adapting different CCT levels throughout the day can have positive physiological and psychological impacts. For instance, exposure to a higher CCT such as 6,500K in the morning can help energize the body and promote wakefulness. Conversely, using a lower CCT around 2,700K in the evening helps support the natural circadian rhythm and prepares the body for rest (Shishegar and Boubekri, 2022).

In conclusion, a dynamic application of different CCT levels tailored to specific times during the day can enhance the visual perception and human well-being.

2.2.5. M-EDI

Melanopic Equivalent Daylight Illuminance (M-EDI) is an index to measure how strong the light source stimulates the non-visual system in the body. This system influences essential biological processes like circadian rhythms, sleep, alertness, and hormone secretion such as melatonin. M-EDI is measured in the unit of lux and serves as a benchmark to assess how potent the light is influencing the biological clock and its corresponding physiological responses within the human body. The amount of Melanopic lux is dependent on the intensity of the light and the correlated colour temperature (CCT). And its corresponding physiological responses within the human body. Melatonin, a pivotal hormone in regulating the biological clock and, consequently, circadian rhythms, is particularly sensitive to the quantity of light, especially at shorter wavelengths, which are perceived as cooler light or a higher CCT, reaching the eyes directly. Consequently, exposure to lower CCT light, which is less biologically stimulating, is recommended during evening hours. In such contexts, maintaining melanopic lux levels below 10 lux is advisable to prevent the light-induced suppression of melatonin, thereby promoting relaxation.

In a work environment, higher CCT and light intensity levels may be advantageous. These conditions can supress melatonin production causing a higher level of concentration and alertness. Under these considerations, melanopic lux levels exceeding 10 Lux are recommended to raise the alertness and energy like offices or schools. (Zisapel, 2018; Houser and Esposito, 2021a; Brown *et al.*, 2022)

2.3. Mood Evaluation

Mood is the manifestation of retrospective affect, along with the cognitive signals, psychophysiological, biochemical process and subjective reactions (Thayer, 1990). This definition highlights the importance of the individual feelings as an indicator of physiological changes, which in turn highlights the value of qualitative methodologies for understanding experiences within real-world environments.

Emotions are regarded as multi-modal psychophysiological systems, comprising at least 4 differentiable components; the subjective (such as feelings of relaxation), the physiological (such as activation of nerve system), the expressive (like facial expressions), the behavioural (runaway from danger) (Watson, 2000). Within affective research, particular emphasis is often placed on subjective and physiological components for their capacity to provide direct insights into an individual's internal state.

In recent years, the design of experimental methodology aimed at investigating behavioral science in real life settings, outside the confines of traditional psychology laboratories, has gained increasing attention(Watson and Vaidya, 2003). This methodological shift acknowledges the complexity of human affective responses within real-world environments, including physical testing contexts such as lighting e how environmental factors influence psychological states.

2.3.1 The Affect Grid

The Affect Grid was designed to assess two dimensions of affect, pleasure-displeasure and arousal-sleepiness. The two dimensions above are the fundamental components of human emotions, which has been approved with the validity within the studies along with psychometric evidence in the assessment of mood (Russell, Weiss and Mendelsohn, 1989). See Figure 6 The Affect Grid, adapted from (Russell, Weiss and Mendelsohn, 1989)

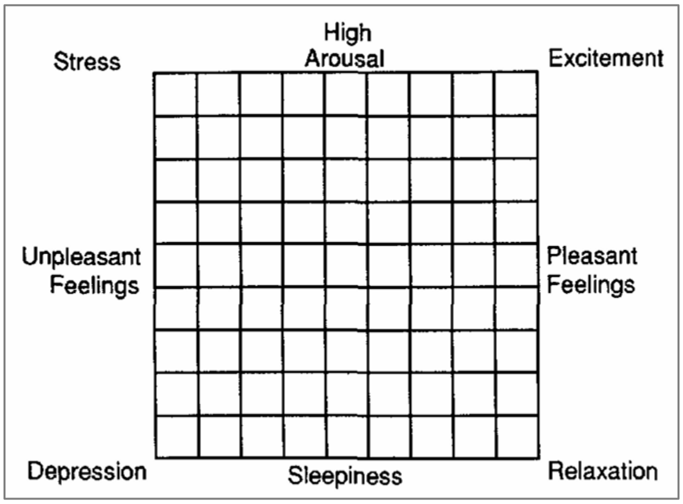


Figure 6 The Affect Grid, adapted from (Russell, Weiss and Mendelsohn, 1989)

Arousal is often referred as activity or activation, consistently emerged as a crucial factor in psychological studies investigating the pleasure–displeasure dimension of emotion. Studies have shown that arousal plays a decisive role in differentiating emotional responses across various contexts, supporting the value in emotion research that relies on self-assessment tools. Therefore, within the current framework, arousal is not merely a physiological marker but a core dimension of how individuals consciously report and interpret their emotional experiences.

2.3.2. The Activation-deactivation Adjective Check List

A variety of established research instruments are available for assessing mood and emotional fluctuations, each varying in terms of temporal sensitivity, emotional dimensions measured, and practical applicability. The Initial method evaluation has been conducted with the selection from the chapter of reviewing the 10 significant measures of affect dimensions (Boyle *et al.*, 2015) and focused on factors such as administration duration, emotional measures, and the methodology to environmental psychology with real life experiments. Among these, the Activation-Deactivation Adjective Check List (Thayer, 1986)and the UWIST Mood Adjective Checklist (Matthews, 2014)are particularly prominent. Both are designed to capture transitory mood states, making them suitable for experimental setups involving environment with the controlled scenarios within the short timeframe. Figure 7 Mood evaluation method comparison, shows the mood evaluation method comparison considered the factors like time, measures and relevance of this study.

Evaluation Method	Description	Time period	Measures	Note
Affect Grid	A quick means of assessing a current affective status.	5s	pleasure–displeasure and arousal–sleepiness	
Melbourne Curiosity Inventory (Naylor, 1981/2011)	The MCI C-State and C-Trait scales comprise 20 items each, but different instructions.		Satisfactory, curiosity	
State-Trait Personality Inventory (Spielberger, Ritterband, Sydeman, Reheiser, & Unger 1995)	The 80-item STPI includes 10 items for each of eight state and trait scales (Spielberger et al., 1995).	>5mins	Anxiety, Depression, Anger and Curiosity	
Positive and Negative Affect Schedule Expanded Form (Watson & Clark, 1999)	The PANAS-X measures both Positive Affect (PA) and Negative Affect (NA), as well as 11 primary affects labeled: Fear, Sadness, Guilt, Hostility, Shyness, Fatigue, Surprise, Joviality, Self-Assurance, Attentiveness, and Serenity.	5mins	transitory emotions, longer-lasting, mood states	
Differential Emotions Scale (Izard, 1991; Izard et al., 1993)	The 36 items are grouped into 12 subscales labeled: Interest, Joy, Surprise, Sadness, Anger, Disgust, Contempt, Self-Hostility, Fear, Shame, Shyness, and Guilt (Izard et al., 1993, p. 851).	>5mins	Lasting mood	
Profile of Mood States (Heuchert & McNair, 2012)	The original POMS (McNair, Lorr, & Droppleman 1992; Lorr, McNair, & Heuchert 2003) which measured 6 mood states labeled: Tension-Anxiety, Depression-Dejection, Anger-Hostility, Vigor-Activity, Fatigue-Inertia, and Confusion-Bewilderment,		'allows for the rapid assessment of transient and fluctuating feelings, as well as relatively enduring affect states.' It provides measures of 7 clinically important mood state dimensions.	
Multiple Affect Adjective Check List-Revised (Zuckerman & Lubin, 1985; Lubin & Zuckerman, 1999)	The MAACL-R comprises 132 adjectival measures of affects. Both state and trait instructions are provided using identical adjective lists.	>5mins	'the State Form asks subjects to describe how they feel 'now-today,' the Trait Form asks them to check adjectives describing how they 'generally feel.'	
Multidimensional Mood-State Inventory (Boyle, 2012)	The MMSI includes five separate self-report scales purported to measure Arousal-Alertness, Anger/Hostility, Neuroticism, Extraversion, and Curiosity.	5-8mins	transitory emotional states	
Activation-Deactivation Adjective Check List (Thayer, 1989)	A multidimensional self-report adjective checklist that is purported to measure transitory arousal states labeled: Energy, Tiredness, Tension, and Calmness. General arousal theories (cf. Pfaff, 2006) concern transitory arousal states such as energetic arousal (general activation), tense arousal (high activation), calmness (general deactivation), and tiredness (deactivation-sleep) (Thayer, 1989; Thayer, Takahashi, & Pauli,1988).	1-2 mins	immediate feelings of activation and deactivation	More aligned with the parameters to the model for EEG signals
UWIST Mood Adjective Checklist (Matthews et al., 1990)	The UMACL is comprised of 29 adjectives, eight for each of the scales, and five for Anger-Frustration. The UMACL is an adjective checklist that assesses mood, building on three-dimensional, Energetic Arousal, Tense Arousal and Hedonic Tone.	2-3 mins	Transitory emotional states	The evaluation scale might be a bit ambiguous.
Dundee Stress State Questionnaire (Matthews, Hillyard, & Campbell 1999, 2002)	The DSSQ aims to assess affective, motivational and cognitive aspects of the states experienced in performance settings. It includes the 3 principal mood scales of the UMACL (see above), two motivational scales (Intrinsic Interest and Success Striving), and six cognitive scales. These are Self-Focus, Self-Esteem, Concentration, Confidence and Control, Task-Related Cognitive Interference and Task-Irrelevant Cognitive Interference.	>5mins	Cognitive states in performance	

Figure 7 Mood evaluation method comparison

Above the theoretical research sections, the selection of the AD ACL and the Affect Grid in this study has been applied in both methodological and practical considerations. The Affect Grid offers a rapid, single-item measure of mood along the dimensions of arousal and valence(Russell, Weiss and Mendelsohn, 1989), making it especially efficient for repeated measurements in real-time lighting tests. The AD ACL, in contrast, provides a more detailed account of arousal-related mood states, thus enabling a nuanced understanding of participants' psychophysiological responses to lighting variations. Previous studies suggest that instruments like the AD ACL, which offer greater differentiation between dimensions such as tension, calmness, energy, and tiredness, may be more sensitive to subtle environmental effects (Thayer, 1986). Figure 8 gives an overview of the AD ACL and the adjectives used to score the different emotions.

ACTIVATION–DEACTIVATION ADJECTIVE CHECK LIST (SHORT FORM)

Each of the words on the back describes feelings or mood. Please use the rating scale next to each word to describe your feelings at this moment.

Examples

Work rapidly, but please mark all the words. Your first reaction is best. This should take only a minute or two.

relaxed	vv v ? no	If you circle the double check (**vv**) it means that you *definitely* feel relaxed *at the moment*.
relaxed	vv v ? no	If you circle the single check (**v**) it means that you feel slightly relaxed *at the moment*.
relaxed	vv v ? no	If you circled the question mark (**?**) it means that the word does not apply or you cannot decide if you feel relaxed *at the moment*.
relaxed	vv v ? no	If you circled the (**no**) it means that you are *definitely not relaxed at the moment*.

(Back page)

Work rapidly, but please mark all the words. Your first reaction is best. This should take only a minute or two.

active	vv v ? no
drowsy	vv v ? no
placid	vv v ? no
fearful	vv v ? no
sleepy	vv v ? no
lively	vv v ? no
jittery	vv v ? no
still	vv v ? no
energetic	vv v ? no
wide-awake	vv v ? no
intense	vv v ? no
clutched-up	vv v ? no
calm	vv v ? no
quiet	vv v ? no
tired	vv v ? no
full-of-pep	vv v ? no
vigorous	vv v ? no
tense	vv v ? no
at-rest	vv v ? no
wakeful	vv v ? no

Notes: Each item is responded to using the following 4-point scale:
vv = 'definitely feel'; v = 'feel slightly'; ? = 'cannot decide'; no = 'definitely do not feel'.
The AD ACL is scored by assigning 4, 3, 2, and 1, respectively to the 'vv, v, ?' and 'no' scale points, and summing or averaging the five scores for each subscale.
The AD ACL Short Form is reproduced in Appendix A of Thayer (1989) and online at: www.csulb.edu/~thayer/thayer/adaclnew.htm (Retrieved January 5, 2014).

UWIST MOOD ADJECTIVE CHECKLIST

Instructions: This questionnaire is concerned with your current feelings. Please answer **every** question, even if you find it difficult. Answer, as honestly as you can, what is true of **you**. Please do not choose a reply just because it seems like the 'right thing to say'. Your answers will be kept entirely confidential. Also, be sure to answer according to how you feel **AT THE MOMENT**. Don't just put down how you usually feel. You should try and work quite quickly: there is no need to think very hard about the answers. The first answer you think of is usually the best.

Here is a list of words which describe people's moods or feelings. Please indicate how well each word describes how you feel **AT THE MOMENT**. For each word, circle the answer from 1 to 4 which best describes your mood.

	Definitely	Slightly	Slightly not	Definitely not
1. Happy	1	2	3	4
2. Dissatisfied	1	2	3	4
3. Energetic	1	2	3	4
4. Relaxed	1	2	3	4
5. Alert	1	2	3	4
6. Nervous	1	2	3	4
7. Passive	1	2	3	4
8. Cheerful	1	2	3	4
9. Tense	1	2	3	4
10. Jittery	1	2	3	4
11. Sluggish	1	2	3	4
12. Sorry	1	2	3	4
13. Composed	1	2	3	4
14. Depressed	1	2	3	4
15. Restful	1	2	3	4
16. Vigorous	1	2	3	4
17. Anxious	1	2	3	4
18. Satisfied	1	2	3	4
19. Unenterprising	1	2	3	4
20. Sad	1	2	3	4
21. Calm	1	2	3	4
22. Active	1	2	3	4
23. Contented	1	2	3	4
24. Tired	1	2	3	4
25. Impatient	1	2	3	4
26. Annoyed	1	2	3	4
27. Angry	1	2	3	4
28. Irritated	1	2	3	4
29. Grouchy	1	2	3	4

Notes:

The UMACL is available from Gerald Matthews at the Institute of Simulation and Training, University of Central Florida, 3100 Technology Parkway, Orlando, Florida, 32826, USA.

Figure 8 Overview of AD ACL (Thayer, 1986) and UMACL (Matthews, 2014) from the selection in (Boyle et al., 2015)

The integration of both tools supports the testing with rapid responses and ease of use, and the other providing the deeper indicators regarding the ensures a comprehensive approach to assessing mood changes. This dual-method strategy enhances both the reliability and interpretive depth of the study's findings, aligning with the broader aim of capturing the psychological impact of lighting in a structured yet ecologically valid manner.

2.4. EEG Methodology Evaluation

EEG is a field where there are multiple ways to measure and manipulate the data. The methodology differs when it comes to the type of study and the chosen parameters to investigate. Small-scale literature research was conducted to get an overview of the methodology used in egg testing settings. There were 6 literature papers collected, compared and further analysed. (See Figure 9 EEG testing comparison)

In the paper “The effect on emotions and brain activity by the direct/indirect lighting in the residential environment”(Shin *et al.*, 2015), there was a group of 28 participants that consists of 12 females. It was investigated the influence of direct and indirect lighting on the brain and emotion. The methodology it used was a mixed method with EEG reading and self-report questionnaire.

About the testing procedure, it was set up to be within the lighting scenarios in the duration of 4 minutes followed by a 4-minute dark period and 4 minutes in between each scenario to allow the participant to adapt to the surroundings and different light conditions. The EEG readings were collected and filtered, then further compared between the two different scenarios using a paired t-test investigating the subject feelings.

The study “EEG alpha phase shifts during transition from wakefulness to drowsiness” (Kalauzi, Vuckovic and Bojić, 2012) investigated the transition between wakefulness and drowsiness. To capture this transitional phase, the overall duration of the experiment was extended, however for each of the 10 participants, one minute of EEG data was recorded during wakefulness and another during drowsiness. The analysis focused on alpha waves, specifically examining changes in the topographical distribution of alpha phase shifts and phase locking across various electrode sites, rather than solely assessing power distribution. To achieve this, the researchers developed and applied a method for measuring phase shifts in alpha carrier frequencies (CFs) between different EEG channel pairs on the scalp.

The research paper “Brain waves and landscape settings: emotional responses to attractiveness” (Karami *et al.*, 2024) investigated how different elements in the landscape affects individuals’ emotional perception and their corresponding brain activity. For each of the 24 participants, EEG recordings and emotional self-assessments were taken as participants viewed landscape images with 5 distinct elements of attractiveness: mystery, visual openness, landscape or greenness, walkability, and social interaction using the Delphi method. Participants viewed five blocks of images over a seven-minute period per block, with two-minute resting intervals between blocks. The study focused on how these visual changes affected emotional responses, measured by the Self-Assessment Manikin questionnaire, and analysed changes in EEG oscillatory patterns across various frequency bands (including delta, theta, alpha, beta, and gamma) using a 32-channel system. They specifically examined how the power and ratios of different brain wave frequencies changed in response to alterations in these predefined attractiveness elements in the landscape images.

In "Enhancing Lighting Design Through the Investigation of Illuminance and Correlated Colour Temperature's Effects on Brain Activity: An EEG-VR Approach" (Mostafavi, Cruz-Garza and Kalantari, 2023), the authors employed virtual reality (VR), EEG, and machine learning to examine the relationship between brain activity and lighting conditions, including illuminance and correlated colour temperature (CCT). Twenty-five participants experienced 17 different lighting scenarios in a virtual office environment via VR headset. For each scenario, participants were allowed to adjust the lighting to their preferred illuminance and CCT levels before proceeding to the next.

Each scenario lasted 10 seconds, with the full session lasting approximately 20 minutes. EEG data were collected using a 22-channel system, focusing on band-power features in the frontal and parietal regions. Machine learning algorithms were used to predict participants' lighting preferences based on their neural responses.

The study "Analysis of Human Electroencephalogram Features in Different Indoor Environments" (Guan *et al.*, 2020) exposed eight healthy participants to two distinct environmental conditions in a controlled climate chamber, one considered comfortable and the other uncomfortable, manipulating factors such as temperature, lighting, and sound. For each condition, participants completed a self-report comfort questionnaire and underwent a five-minute EEG recording using a 64-channel system following a 15-minute adaptation period. The analysis included statistical comparisons of total EEG energy across conditions.

Finally, "An Evaluation of Emotions Induced by Biophilic Lighting Colours Using EEG and Qualitative Methods to Support Community Well-Being in Urban Spaces" (Hill and Triantafyllidis, 2023) adopted a mixed-methods approach to investigate emotional responses to biophilic lighting colour schemes. Five participants were exposed to various coloured biophilic lighting patterns for 60 seconds each, separated with a 30-second neutral spotlight as a control scenario. EEG recordings focused on alpha and gamma band power, complemented by responses to an adapted Discrete Emotions Questionnaire (DEQ). EEG data were analysed by averaging alpha and gamma power per second, calculating percentage changes from control conditions, and aggregating results across participants to map responses onto a valence-arousal model. DEQ results were similarly normalized against the control condition for comparative analysis.

PAPER	Quantitative data	Qualitative data	Participants	Pre test	Test Length	In Between
The effect on emotions and brain activity by the direct/indirect lighting in the residential. (Shin et al., 2015)	EEG » single electrode power » paired t-tests	Self-report survey visual analog scales Self-Assessment Manikin	28	0Lux 4min	2 scenarios Exposure 4min	0Lux 4 min
EEG alpha phase shifts during transition from wakefulness to drowsiness. (Kalauzi, Vuckovic and Bojić, 2012)	EEG » Alpha power analysis » Phase shifting		10		1min EEG reading	
Brain waves and landscape settings: emotional responses to attractiveness (Karami et al., 2024)	EEG » Oscillatory pattern » Single electrode power	Self-report survey Manikin questionnaire	24		7min	2min
Enhancing lighting design through the investigation of illuminance and correlated color Temperature's effects on brain activity: An EEG-VR approach (Mostafavi, Cruz-Garza and Kalantari, 2023)	EEG » Band power analysis » Machinelearning	Questionnaire Interview	25	Eys 1min closed 1min open	17 scenarios Exposure 10s	
Analysis of human electroencephalogram features in different indoor environments (Guan et al., 2020)	EEG » Total EEG energy	Self-report Questionnaire	8	15min	5min	
An evaluation of emotions induced by biophilic lighting colours using EEG and qualitative methods to support community well-being in urban spaces (Hill and Triantafyllidis, 2023)	EEG » Percentages band power	Discrete Emotions Questionnaire	5		1min	30 seconds
Average			16.6		2.1 min	2.25 min

Figure 9 EEG testing comparison

Based on the six papers analyzed in Figure 9, it is evident that the methodologies vary considerably across studies. Differences were observed not only in how EEG data were recorded and interpreted, but also in the number of participants involved and the duration of the experiments.

This brief literature review was conducted to provide an overview of the diverse approaches used in EEG-based research. It also serves as a foundation for establishing methodological benchmarks and guiding the design of future experiments

3. Methodology

The methodology employed in this study is a mixed-methods approach, combining both quantitative and qualitative data analysis to develop a comprehensive understanding of how light intensity and luminance, originating from direct and indirect light sources, affect physiological and psychological responses related to relaxation and emotional well-being within the context of the home environment as stated in section 1.2.1. Research Question. The methodology applied is sown in Figure 10 to give an overview.

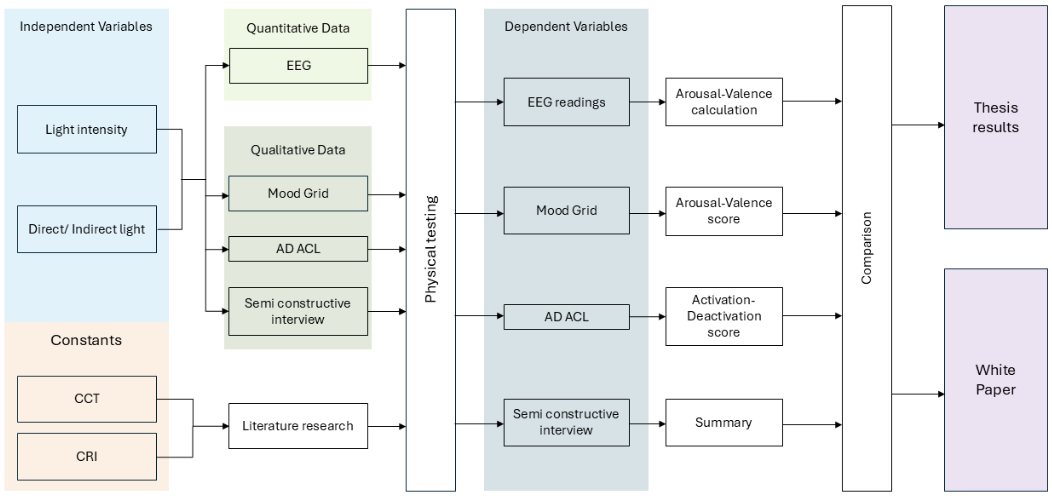


Figure 10 Methodology overview

The physical testing is the core of this methodology where Light intensity and Direct/indirect lighting are the tested variables (Independent Variables). Bot quantitative and qualitative data gathering methods are used to measure the response (Dependent variables). The results from each variable are then compared to conclude an overall result. The quantitative and qualitative data are linked to see if the influence of the different independent variables is aligned across the physiological and psychological response.

3.1. Participants

A total of 26 individuals volunteered to participate in the study. The sample included 16 women and 10 men. In terms of age distribution, 20 participants were between 25 and 30 years old, 4 participants were aged 20 to 24, and 2 participants were between 30 and 34. The mean age of the participants was 26.5 years, with an age range of 20 to 34 years.

Regarding handedness, one participant identified as ambidextrous, one reported being primarily right-handed but capable of using both hands for certain activities, two identified as left-handed, and the remainder were right-handed. Participants were primarily recruited from the student population at Aalborg University in Copenhagen, with some joining through referrals from friends or partners who had already agreed to participate. At the time of data collection, all participants were informed about the general purpose of the study and understood that it involved non-invasive brain data collection with EEG headset. Of the 26 initial volunteers, three participants were excluded due to scheduling conflicts, resulting in 23 eligible participants. Of these, two participants were allocated to pilot testing to evaluate and refine the experimental procedure and scenarios. Additionally, one participant did not attend due to illness. This resulted in a final sample of 20 participants for the actual experimental testing and data collection

3.2. Registration Survey and Self-reported Survey

During participant recruitment, a registration form was utilized to manage the limited number of daily testing slots available at the Muuto showroom this form collected personal information, handedness, and any pre-existing psychological health conditions that might contraindicate EEG assessment, given that EEG may not be suitable for individuals with certain neurological or medical conditions. The form also allowed prospective participants to indicate their availability in predefined timeslots.

The selection of these timeslots was guided by the availability of the testing site (Muuto Showroom) and a realistic timeframe accommodating participants' availability, typically after standard work hours. Three timeslots were established for each workday over a two-week period, resulting in 30 potential timeslots distributed across 10 days. This quantity of timeslots was determined to achieve the target sample size of at least 17 participants, a figure derived from the average participant numbers reported in six relevant studies employing EEG experimentation (2.4. EEG Methodology Evaluation).

After we arranged every participant into the schedule, they would receive a confirmation letter with the time, participation number (to ensure privacy during data collection of personal data), and pre-test instructions to be aware of, like not consuming coffee and nicotine products before the test.

To further understand potential subjective biases and their possible influence on EEG outcomes, a secondary "Self-Reported Survey for EEG Test" was administered. This survey was designed to provide a general overview of participants' relevant health factors and comprised five main sections:

(1) General information and link to a consent form about personal data handling. This first part contained a field where they wrote the participant number they were assigned from the fist conformation email.
(2) Personal health status like workout habit, nicotine and alcohol use and usual sleeping pattern.
(3) Health and medical history such as neurological diseases, serious head injury and sleeping disorder.
(4) Information about prior experience with EEG and information of any skin allergy to gels, such as those used with EEG headsets.
(5) A checklist of pre-test preparations, reiterating advice such as ensuring adequate sleep and abstaining from caffeine and nicotine substances prior to the test.

Analysis of the self-reported data revealed the following findings:

In terms of sleeping habits, approximately 50% of participants reported feeling well-rested with 8 hours of sleep, 30% with 7 hours, and 15% with 6 hours. Additionally, three participants reported a history of insomnia, while two indicated experiencing sleep apnoea. Regarding stimulant intake, four participants reported regular cigarette use, and one participant used a nicotine patch daily. Furthermore, 13 participants consumed caffeinated beverages such as coffee or tea daily. In terms of medical history, four participants disclosed either a diagnosis or a suspicion of attention deficit hyperactivity disorder (ADHD). No other significant neurological disorders were reported.

All participants provided informed consent prior to their involvement in the study. They were made aware of the data collection procedures and the intended use of the data for thesis research. No personal data will be disclosed to any third parties outside of the academic institution.

3.3. Measure

3.3.1. 8-channel Wearable EEG Headset

The primary equipment utilized for brain signal acquisition was the 8-channel Unicorn Hybrid Black EEG headset, coupled with the Unicorn BCI Core, developed by g.tec medical engineering GmbH (g.tec Medical Engineering, Schiedlberg, Austria). This system operates at a sampling rate of 250 Hz and its electrode placement conforms to the international 10–10 system (2.1.1. 10/10 System). The eight primary EEG channels monitored via the headset's electrode sensors are Fz, C3, Cz, C4, Pz, PO7, Oz, and PO8. Accompanying the EEG headset, Unicorn Bandpower, a compatible preprogrammed application, was employed to visualize the brainwaves from these eight scalp positions. This software continuously measures bandpowers across several frequency ranges: delta (1–4 Hz), theta (4–8 Hz), alpha (8-12 Hz), low beta (12–16 Hz), mid-beta (16–20 Hz), high beta (20–30 Hz), and gamma (30–50 Hz). By default, the Bandpower application is configured with a buffer of 250 samples and a buffer overlap of 240 samples, resulting in a 25 Hz update rate for the bandpower features (*GitHub - unicorn-bi/Unicorn-Bandpower-Hybrid-Black: Unicorn Bandpower Hybrid Black*, 2025).

The acquired brainwave data were recorded and stored in CSV file format for subsequent offline processing. This processing included a second-order Butterworth bandpass filter, with a frequency range of 0.5 Hz to 50 Hz, to the raw data. Figure 11 illustrates the 10–10 EEG system, with red circles indicating the specific channel locations utilized by the Unicorn EEG headset in this study.

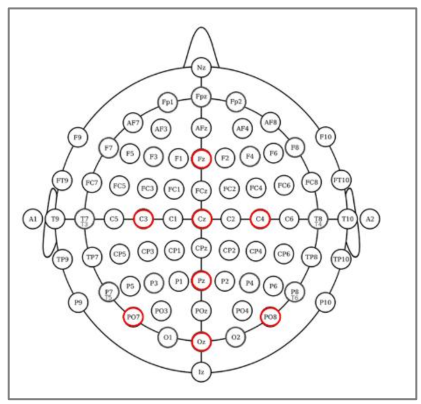


Figure 11 EEG Electrode position

The Unicorn EEG headset was selected in this research as for its versatility and user-friendly data storage and transcript. It is more adaptable with its wearable Bluetooth device for physical experience in different scenarios, and the 8 channels to collect EEG signal from the frontal, parietal and occipital lobes, and the central sulcus, which is within the scope of arousal and valence related calculations (2.1.1. 10/10 System). There is some research papers related to the EEG and human interaction through the same model headset for measurement, such as a study about the brain engagement using EEG signals for hand rehabilitation in games (García-Ramón *et al.*, 2024), a study to analyze human emotions during the interaction with a social robot using EEG, arousal and valence method (Staffa *et al.*, 2023).

3.3.2. Mood Evaluation Questionnaire

The aim for this study is to unfold the influence of lighting parameters have on the human physiological and psychological response. In the book "The Biopsychology of Mood and Arousal" Thayer stated "subjective feelings are somehow regarded as the last processes in a chain of more important physiological changes. In my view, however, subjective feelings, thoughts, and psychophysiological and biochemical processes all interact together, and each has its own necessary function in ongoing behaviour."(Thayer, 1990). The mood is a result of cognitive signals, psychophysiological and Biochemical processes, and subjective preferences, which we chose to collect for an overall understanding the emotions of participate retrospectively.

The right methodology to measure the physiological response is crucial. The design needs to be easy to understand and intuitive to record participant's subjective emotional state. Informed by a review of various qualitative measurement methodologies detailed in Section 2.3. Mood Evaluation, two specific questionnaire types were chosen for this study.

The mood evaluation questionnaire in this study integrated two established frameworks: the Affect Grid (Russell, Weiss and Mendelsohn, 1989) and the Activation-deactivation adjective check list (Thayer, 1986). The first component of the questionnaire was the "Mood Grid," a 20x20 grid featuring indicative words along its axes (typically representing valence and arousal). Participants were instructed to select a single cell within the grid that best represented their current mood state in real time, immediately following exposure to each distinct lighting scenario. Figure 12 illustrates the Mood Grid, which captured participants' immediate emotional responses based on the arousal–valence model.

The second component consisted of a mood checklist derived from the AD ACL. This checklist presented adjectives, each accompanied by a four-point rating scale:

(i.e. (vv) = "definitely feel", (v) = "slightly feel", (?) = "cannot decide", (no) = "definitely do not feel").

From the original 20 words typically found in the AD ACL 4 adjectives (full-of-pep, jittery, clutched-up, placid) were selectively eliminated. Thil modification was done because the vocabularies are not common in daily lives and would influence the reaction time of participate. The original 20-item AD ACL (Thayer, 1986), comprises of five adjectives in each of the four subscales (i.e. Energy, Tiredness, Tension, Calmness). This scale is then scored from 1 ('Definitely Do Not Feel') to 4 ('Definitely Feel'), adhering to the standard instructions recommended by (Thayer, 1990)were used. Figure 13 represents the second part of the mood evaluation and categorizes emotional states into four dimensions: Energy, Tiredness, Tension, and Calmness. These scores were used to assess variations in emotional response across different lighting scenarios.

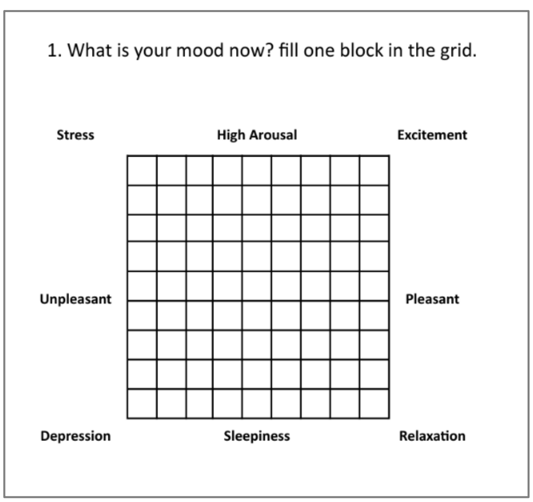


Figure 12 Mood Grid

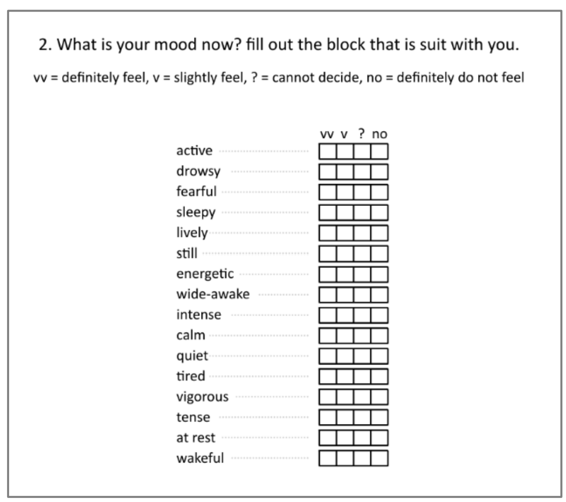


Figure 13 Mood check list

3.3.3. Semi-constructive Interview

After completing all four lighting scenarios and the corresponding EEG recordings, participants were asked a series of questions regarding their overall experience, including their mood, emotional responses, and lighting preferences under each condition. To account for individual variability, factors such as each participant's health status, sleep quality, and recent lifestyle habits were documented and preserved as reference data for potential use in the analysis.

3.4. Participation of Muuto

A collaboration with Muuto was established for the practical experiment phase of this thesis. Muuto provided access to their showroom facilities and their available lighting fixtures, which served as the environmental setting for the testing.

Muuto is a Danish furniture company that is rooted in Scandinavian design traditions. Their focus is honest design that stimulate the senses and evoke feelings by a simple and familiar design.

"Our interiors are landscapes for authentic and analogue experiences. Our homes are filled with objects that stimulate the senses. Colores that evoke memories and emotions. Materials that trigger feelings. Shapes that tap into our subconscious. Objects influence our impression of space and how we feel when in the presence of them." (*Muuto - Our Story*, 2025) . Muuto's approach of how object and lighting are influencing our emotions and wellbeing are well aligned with the aim of this research.

The experimental design was developed independently and Muuto had no interference in the formulation of the research question, the design of the experimental methodology, the selection of the lighting fixtures or the analysis or interpretation of the data.

The collaboration with Muuto was based on the aligned objective to create a home environment that facilitates a restorative space and benefit both parties in creating the awareness of the visual and non-visual effects in the residential context.

3.5. Test Settings

The testing environment was designed and set up within a designated area of the Muuto showroom. The space measured 1.2 meters in length, 5 meters in width, and 3 meters in height he setting replicated a cozy living room, incorporating a selection of furniture and décor elements to simulate a realistic domestic atmosphere. The layout included one stacked storage bookshelf, two lounge chairs, one three-seat sofa, one sofa table, one coffee table, and three plants—two placed in the corners and one positioned atop the bookshelf.

The design of the testing environment considered the flexibility of fixture placement aiming to enhance light reflection, atmospheric quality, and variety in luminous expression. The scenarios are imitating cozy living room settings with furniture used for reflecting the light, enhancing the atmosphere and increase the variety of luminous methods. Within the testing design, one of the lounge chairs is used for the seating for participant with designated view direction, another one used for atmospheric purpose; the bookshelf with 12 blocks was used to increase different lighting solutions and interior decorations; the plants were also used for reflective and shadow-casted effects to create the connection of space and light (2.2.1. Visual Element of Light)

To ensure control over the light conditions were all ambient daylight and unrelated spotlights in the office outside of the testing area excluded. This was done by thoroughly draping the perimeter of the space with heavy black curtains. After the pilot test the first day an inner layer with white curtains were introduced to raise the overall brightness and diffuse light more effectively within the testing space (see the interior display in Figure 14).

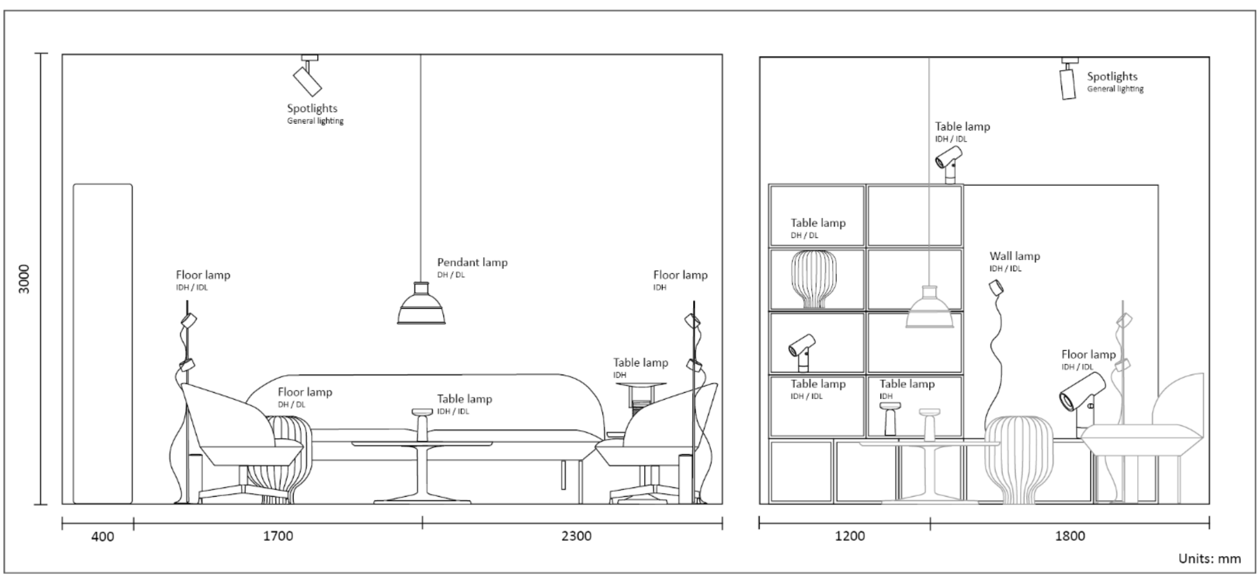


Figure 14 The graph shows the dimensions of the testing space in two different section plans.

There are four lighting testing scenarios, which are direct light with high intensity, direct light with low intensity, indirect light with high intensity and indirect light with low intensity, with the abbreviation for DH, DL, IDH, IDL for the rest of the paper if mentioned (see the four lighting scenarios in Figure 15).

Figure 15 The four lighting scenarios with DH, DL, IDH, IDL.

The fixtures used in the four different lighting scenarios all the fixtures were selected from Muuto selection beside the general lighting in the control scenario.

Direct illuminance in scenario: DH and DL 3 typed of fixtures was selected, Strand Floor H59, Strand Table H39 and Unfold Translucent. These fixtures demanded a light bulb where we used Philips hue that allowed us to control the intensity and CCT. At both high and low intensity, the CCT was set to be 2700K, high intensity was set to 95% brightness that resulted in M-EDI of 25lux. Low intensity was set to 25% brightness resulting in M-EDI of 4lux.

Indirect illuminance scenario: IDH and IDL 6 typed of fixtures was selected, these fixtures has built in LED module and a fixed CCT of 2700K with the ability to be dimmed up and down illustrated in Figure 16. light scenario IDH has 9 indirect luminaires in their full brightness to reach 25 melanopic lux.

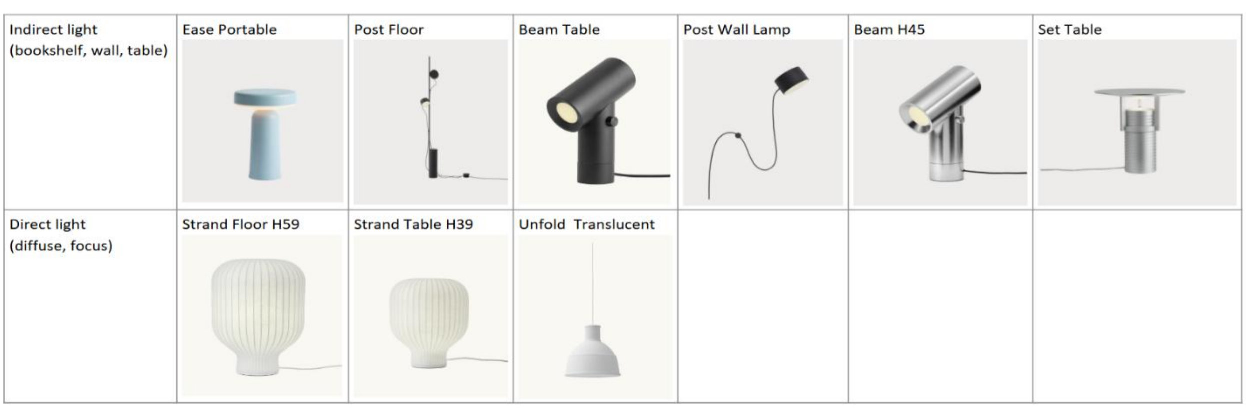


Figure 16 The chart above shows the chosen luminaires from Muuto in the lighting scenarios with direct and indirect directionality.

light scenario IDL has 6 indirect luminaires dimmed down to the lowest level with 3 turned off to reach a M-EDI of 4lux as shown in Figure 16.

The general lighting contains of 3 rail spotlights in their full brightness and measured within 3000K CCT range that produced 36 melanopic lux.

The reflectance of all relevant surfaces within the testing area was measured and calculated to ensure accurate control of lighting conditions. Reflectance is defined as the ratio of surface radiance (light reflected by a material) to surface irradiance (light incident on the material) and typically ranges from 0 to 1. For clarity, these values are presented as percentages, where 100% indicates full reflectance.

The measured reflectance values are as follows:

Curtains: Thin white – 42%, White – 46%, Black – 7%

Grey wall: 28%

Ceiling: 82%

Furniture surfaces: Carpet – 20%, Table – 18%, Sofa – 21%, Bookshelf – 28%

A significant change in reflectance was observed when replacing the white curtain with a black one, indicating a substantial reduction in reflected light within the space. These differences directly impact the distribution and quality of illumination in the environment.

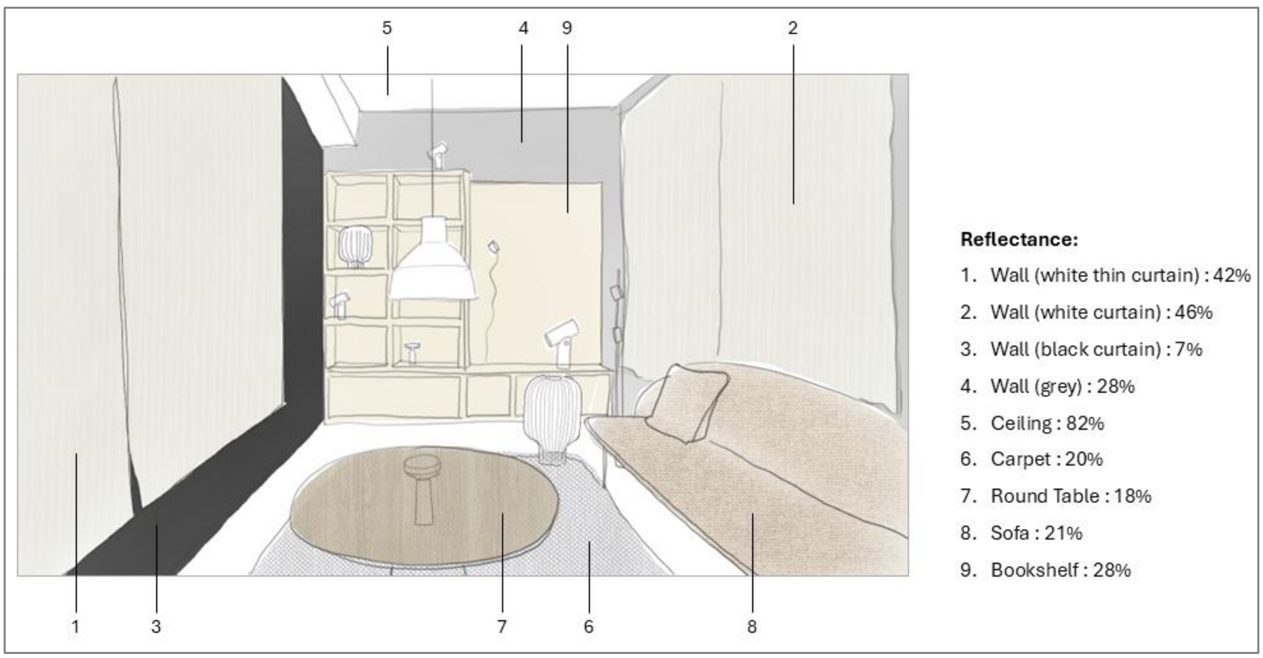


Figure 17 The reflectance ratio for every material surface

3.6. Test Procedure

The testing was conducted over a period of eight days, specifically from March 24th to 27th and March 31st to April 3rd, between 18:00 and 21:00 each day. Each session lasted approximately 40 to 60 minutes per participant, including the EEG headset setup and a post-test interview segment. Due to spatial constraints and the shared use of the Muuto showroom, the testing environment had to be set up and packed down daily. Since the position of luminaires and furniture, weather conditions and the LED fluctuations may differ in different testing days, key lighting parameters were measured prior to each session. To control the affecting factors within an acceptable range, every scenario had been measured every time before the testing with spectrometer from GL Optics. The assessed light parameters including CCT (Colour Correlated Temperature), CRI (Colour Rendering Index) and M-EDI (Melanopic Equivalent Daylight Illuminance) with the scenarios in high intensity of 25 lux and low intensity of 4 lux. The related numbers for control environment are documented and calculated as following: the mean of CCT in every scenario within the testing days is 2674 with a standard deviation of 187K; the mean of M-EDI in the setting for high intensity is 24.86 lux with a standard deviation of 0.88 lux; for low intensity is 3.87 lux with a standard deviation of 0.46 lux; while 3004K in CCT and 36.6 in M-EDI within the general lighting in between every testing scenario as a transition control environment. (Figure 19 and Figure 18 are the controlled parameters every testing day)

	DH	DL	IDH	IDL	General
3/24					
CCT (K)	3187	5182	3237	4674	
EML (lx)	26.83	15.65	24.17	16.02	
M-EDI (lx)	24.34	14.21	21.92	14.54	
3/25					
CCT (K)	2697	2581	2560	2483	
EML (lx)	26.59	4.15	28.28	4.75	
M-EDI (lx)	24.09	3.75	25.62	4.28	
3/26					
CCT (K)	2678	2499	2547	2448	
EML (lx)	26.25	4.43	27.72	3.56	
M-EDI (lx)	23.78	4.01	25.12	3.21	
3/27					
CCT (K)	2708	2654	2564	2549	
EML (lx)	26.67	3.89	26.94	3.69	
M-EDI (lx)	24.17	3.54	24.43	3.35	
3/31					
CCT (K)	2742	3366	2633	3073	3022
EML (lx)	27.24	4.47	28.07	5.77	40.33
M-EDI (lx)	24.7	4.06	25.45	5.24	36.57
4/1					
CCT (K)	2781	2840	2580	2542	
EML (lx)	28.12	4.38	30.15	4.21	
M-EDI (lx)	25.48	3.97	27.33	3.81	
4/2					
CCT (K)	2774	2787	2599	2639	
EML (lx)	27.33	4.09	26.4	4.13	
M-EDI (lx)	24.77	3.72	23.94	3.75	
4/3					
CCT (K)	2774	2741	2575	2480	
EML (lx)	26.92	4.01	27.31	4.29	
M-EDI (lx)	24.41	3.63	24.75	3.89	

	CCT	M-EDI (H)	M-EDI (L)
Average	2674.8	24.86	3.87
Variance	35248.03	0.79	0.22
Standard Deviation	187.74	0.89	0.47

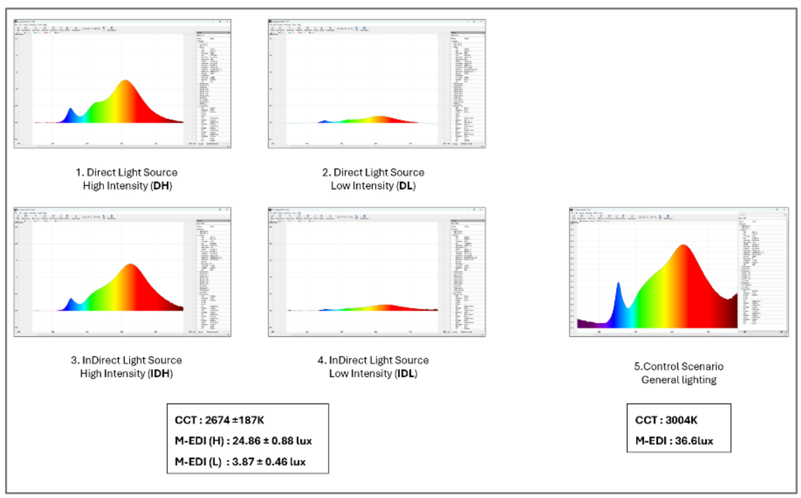


Figure 19 The measurement graph extracted from spectrometer showing the light parameters including CCT, CRI and M-EDI.

Figure 18 The chart is the measurement of CCT, M-EDI, EML within the testing days

For each participant 60 minutes were allocated for the whole test procedure. 15 minutes was used to brief each participant while they were fitted with an EEG headset, and electrode impedances were balanced using conductive gel to ensure signal consistency. During this time participants were introduced to the mood evaluation questionnaire, allowing them to familiarize themselves with the process and reduce any anxiety that might influence their mental state.

The core of the test where the participants were exposed to the four randomized lighting scenarios explained in section 3.5. Test Settings

This part of the test took in average 20 minutes, during testing were the participants required to sit still and keep the same viewpoint throughout the whole process. Each light scenario lasted for 3 minutes with a 1-minute transition between scenarios. During the transition were the participants answering the mood questionnaire and the new light setting were prepared before the next light scenario started. Upon completion of all four scenarios, participate were asked a few questions regarding to the light quality, preference of light and feelings for each scenario. These responses were documented in written form and later analysed using cross-methodological comparison techniques. This proses took in general 5 minutes that leaves 20 minutes in buffer to clean the headset and prepare for the next participant. (see Figure 20 for the testing procedure and time)

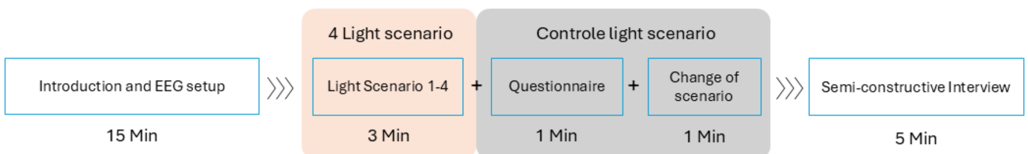


Figure 20 Testing procedure

Figure 21 The luminaires set up during the test

Figure 22 The EEG signal check during the set up

Figure 23 The measuring process after the test execution

Figure 24 Scenario setup with curtains

3.7. Post Data Handling

3.7.1. EEG Data

The data from the testing resulted in 88 CVS files containing data from the 22 participants. Two of the participants the first day were used as a pilot test and that leaves 20 participant (3.1. Participants) with 80 files with data to be analysed. The data were stored as a CSV file the in simple terms look like a excel file with columns and rows containing readings from the EEG.

Each CSV file corresponds to a specific lighting scenario, meaning each participant generated four files, one for each condition: Direct High (D-H), Direct Low (D-L), Indirect High (ID-H), and Indirect Low (ID-L). The CVS files are containing 70 columns with 4500 rows of data that results in over 25 million parameters of data. This amount of data is impossible to handle manually or calculated in a simple excel sheet, some automation is necessary to make it flexible to be able to apply different filtering and Valence, Arousal calculations. As shown on the chart below on Figure 25 is this process divided up in several smaller tasks. All data handling was conducted in Google Sheets, primarily due to its user-friendly interface, compatibility with custom scripting via Google Apps Script, and integration with Google Colab for more complex data processing tasks. Additionally, storing data in the cloud provided an extra layer of security and accessibility, ensuring that data were not dependent on a single physical device.

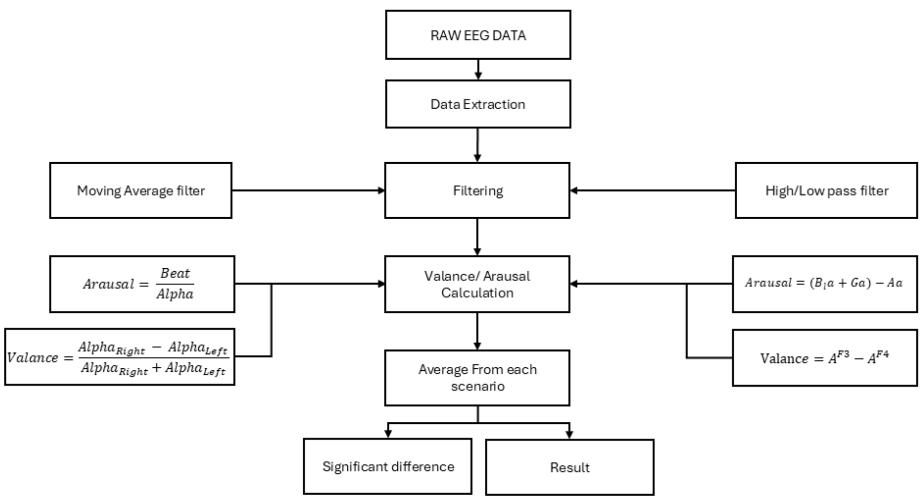


Figure 25 EEG data handling flowchart

3.7.1.1. Data Extraction

Alle 80 CVS files were collected and structured in one single folder in google drive. Since all the 80 files are structured the same in terms of how the data is stored, it was possible to develop a custom script that extracted the relevant columns of data we needed. The files originally contain 70 columns that are readings from each electrode with each frequency as well as average readings. However, for the purpose of valence and arousal calculations, only eight columns were required: Alpha Channel 2, Alpha Channel 4, Alpha Channal 6, Alpha Channel 8, Alpha average, Beta low average, Beta high average and Gamma Average. This script is running in Apps Scrips inside of Google Sheets, it goes through the folder of CSV files and extracts the corresponding columns and puts it in a separate page inside the work sheet. This were both time saving and eliminated problems caused by manually copying the wrong columns.

3.7.1.2. Filtering

Filtering is a critical step in EEG data analysis due to the high sensitivity of the signal. Artifacts caused by eye blinks, facial movements, and even slight muscle activity can result in pronounced spikes in the signal, potentially compromising the reliability of the readings. Poor connection between the electrode and the scalp can create a lot of interference, these anomalies need to be filtered out. In the software that are used with the EEG headset there is already a High-Low pass to remove the most severe signal distortions, post-processing is still necessary to further clean the data and enhance signal quality.

High/Low pass filter is where the data is run through an upper and lower limit, if the values are outside of the given limits, then its deleted. The advantage of this filter is that you can precisely specify what is needed and exclude everything above or below the limits. The downside is that it deletes the value making the total dataset smaller.

Moving average filter is smoothening out the data by averaging the values over a specific window or range. The range or window is how many data points the average are calculated with. The filter is sliding the window over the data, for each point of the data it is calculating the average using the window and applying that value to the data point. This smoothens out the data and has a bigger effect on spikes, see Figure 26 Filtering comparison, of how the data looks with the two different filters.

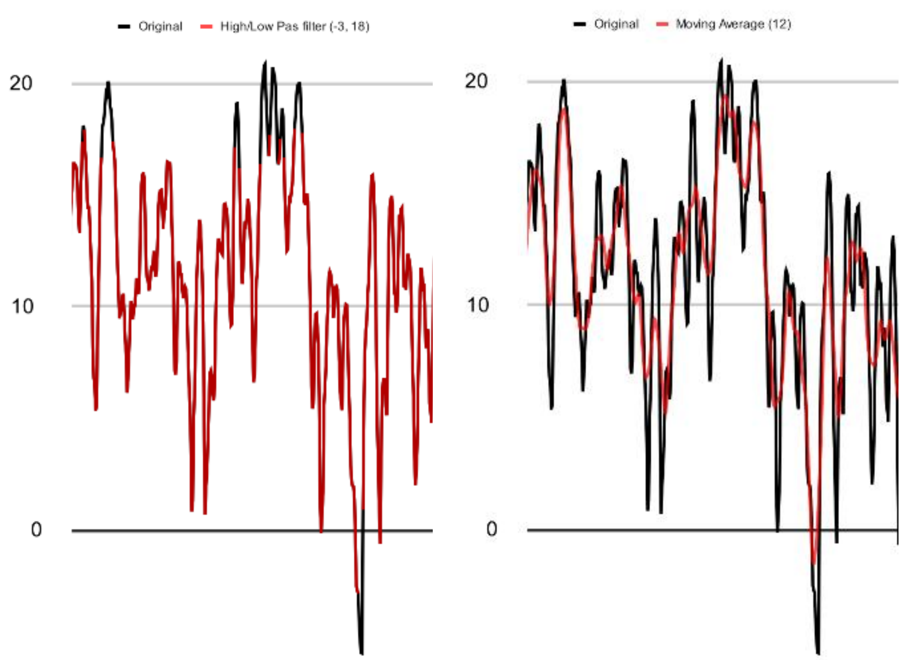


Figure 26 Filtering comparison

In conclusion has both filters' benefits and drawbacks, the essential part it to only filter out data that are caused by movements and not influence the valid data that will give a good result.

3.7.1.3. Valence, arousal calculation

The valence and arousal calculations were conducted using two distinct methods, as outlined in Sections 2.1.3. Arousal Calculation and 2.1.4. Valence Calculation, to facilitate comparative analysis. An overview of both calculation methods is presented in Figure 27. This comparison was performed to verify the results and evaluate the impact of the calculation method on outcome interpretation. As shown in Figure 27, the two calculation types yielded notably divergent results.

$$Arausal(A) = \frac{Beat}{Alpha} \qquad Valance(A) = \frac{Alpha_{Right} - Alpha_{Left}}{Alpha_{Right} + Alpha_{Left}}$$

$$Arausal(B) = (B_l a + Ga) - Aa \qquad Valance(B) = A^{F3} - A^{F4}$$

Figure 27 Valence, Arousal Overview

For valence, Valence (A) indicates that the Indirect Low (IDL) lighting scenario produced the highest positive valence, whereas Valence (B) indicated it had the lowest negative valence. This inversion in results was consistent across all scenarios and is an expected outcome, stemming from the mathematical design of the two formulas. Specifically, Valence (A) calculates the difference by subtracting left hemisphere activity from right, whereas Valence (B) inverts this by subtracting right from left. As a result, Valence (A) tends toward negative values, while Valence (B) yields positive values, even though both represent the same underlying neural activity described in section 2.1.4. Valence Calculation.

A similar inversion pattern is observed in the arousal calculations. For instance, in Arousal (A), both IDH and IDL scenarios exhibit low arousal, while Arousal (B) produces relatively higher values under the same conditions as seen in Figure 28 Valence, Arousal comparison.

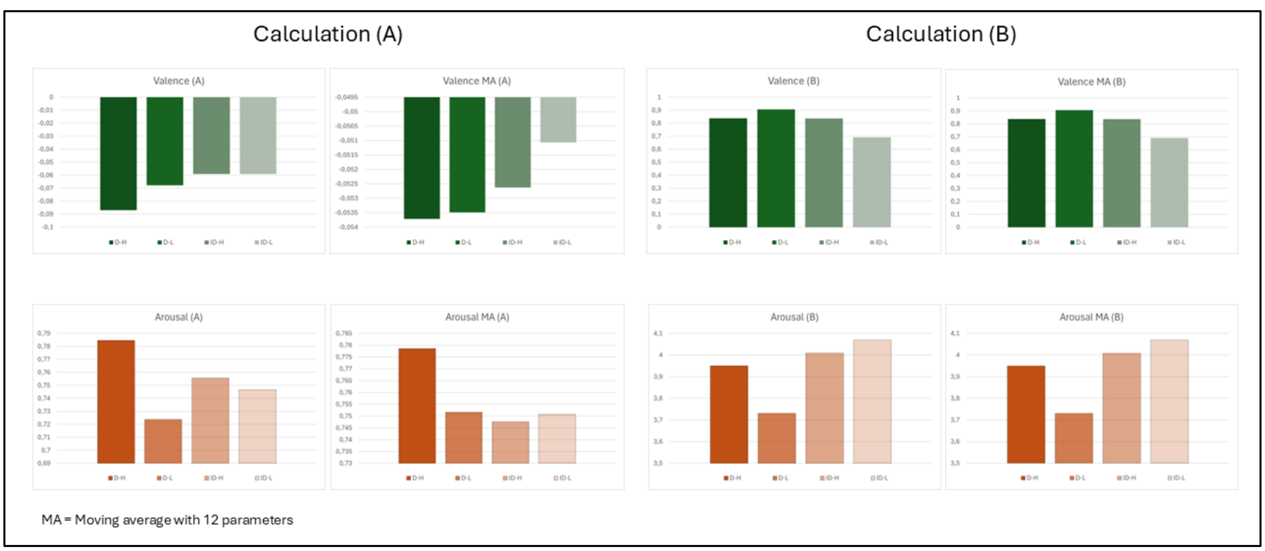


Figure 28 Valence, Arousal comparison

The statistical distribution between the scenarios is calculated by extracting the maximum average value and the minimum average value between each of the four different Valence and Arousal calculations (Valence A/B and Arousal A/B), comparing those differences with and without filtering. These values were then used to compute the range of variation across the four lighting scenarios.

The scenario averages were calculated based on data from all 20 participants. As seen in Figure 29, the analysis confirms that Calculation (B) (both Valence and Arousal) shows no effect from the application of the Moving Average Filter sown by the orange and green column in Valence (B) and Arousal (B) being the same. Calculation (A) shows a noticeable decrease post-filtering: Valence (A) values approach zero, and Arousal (A) is reduced by approximately half compared to the unfiltered data.

It is important to note that the distribution is not indicating anything about the quality of the calculations or anything about the results itself. Only the variation between the different scenarios (DH, DL, IDH and IDL). For example, the result of 0.3382 in Arousal (B) implies that the average arousal values across the four lighting conditions are distributed within a range of 0.338. A smaller number suggests that the scenario results are more closely clustered, whereas a larger value indicates greater variability.

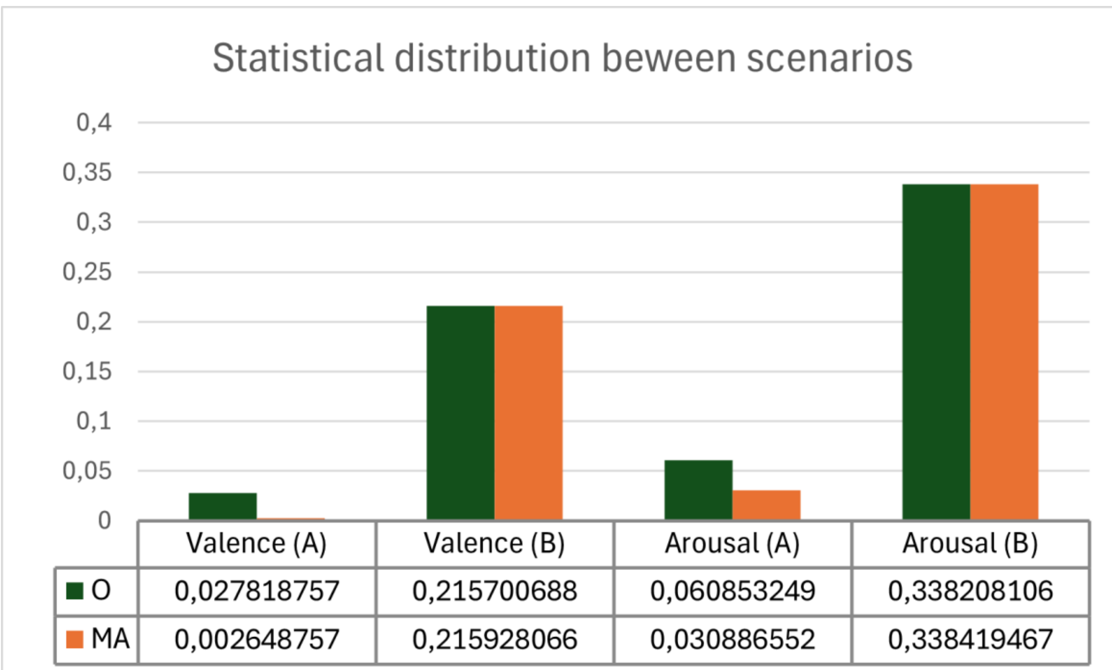


Figure 29 Statistical distribution between scenarios

3.7.2. Mood Evaluation Questionnaire

3.7.2.1. Arousal and Valence Distribution from Affect Grid

The initial phase of the mood evaluation involved documenting responses from all 20 participants (n=20) on a 9x9 Mood Grid. Each cell selected by the participants has been assigned a numeric value based on its position on the x-axis and y-axis both ranging from -4 to 4.

To get an overview of the mood distribution of four different lighting scenarios, an initial analysis involved creating an overlapped mood grid for all participants. Figure 30 shows the Valence and Arousal score of all the participants in each scenario. The bubble plot chart, an extension of the scatter plot, is applied to observe the relationships between three numeric variables. The position of each dot on the horizontal and vertical axis indicates values for an individual data point, which refer to the arousal and the valence, while the colour scale of the dot indicates the number of participants selecting that particular Valence-Arousal coordinate, a darker bubble signified that more participants reported the same affective state.

Participant Number	Valence				Arousal			
	DH	DL	IDH	IDL	DH	DL	IDH	IDL
3	3	-1,5	-2	3	2	-2,5	3	3
4	-3	-3	0	1	2	-2	1	-1
5	-1	2	3	3	1	-1	0	-2
6	1	1	2	3	0	-1	1	-1
7	2	3	2	4	-1	-2	-3	-3
8	2	4	3	3	-1	-3	-2	-1
9	3	3	1	3	2	-3	2	-2
10	0	3	0	2	0	-2	3	3
11	1	1	0	1	1	-3	2	-2
12	3	3	3	4	-1	-3	0	-3
13	-2	3	3	4	1	2	3	-3
14	1	3	-1	2	-1	-3	0	-1
15	1	2	2	1	-1	-4	-2	-2
16	3	2	2	4	2	-2	0	-2
17	1	1	0	3	-3	-4	1	-4
18	-2	1	2	2	-1	-4	-3	-4
19	-1	2	4	2	-1	-2	2	-4
21	3	4	-2	-3	-2	-4	3	-3
22	2	2	3	4	-4	-4	2	-4
23	-2	-1	2	2	-1	-3	2	-2
Median	1	2	2	3	-1	-3	1	-2
Average	0,82	1,66	1,32	2,41	-0,55	-2,62	0,69	-2,05

Figure 30 The chart for overall values from mood grid

Examination of the bubble charts for the different lighting scenarios revealed distinct trends. A generally positive valence trend was observed for three lighting scenarios – DL (Direct High), IDH (Indirect High), and IDL (Indirect Low) – with a greater concentration of data points on the positive x-axis. Conversely, the DH (Direct High) scenario showed fewer data points in the positive valence range, suggesting that direct, high-intensity light tended to elicit lower valence ratings from participants. Regarding arousal, a significant trend emerged in relation to light intensity: higher light intensity generally corresponded with increased subjective arousal, as indicated by a greater distribution of data points on the positive y-axis for high-intensity scenarios. In contrast, for the DL and IDL scenarios, the data points were more concentrated on the negative y-axis. This pattern suggests a positive correlation between light intensity and subjectively experienced arousal levels.

(See the dots distribution in four lighting scenarios in Figure 31 Mood Grid Response)

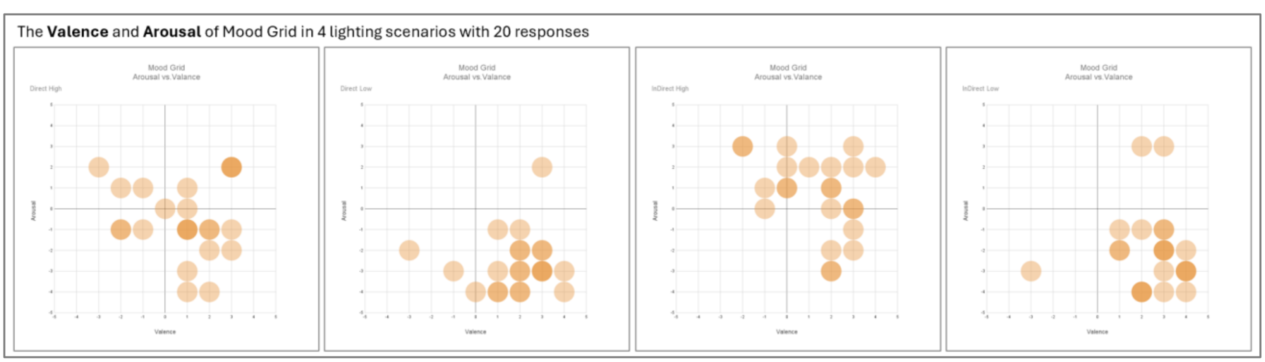


Figure 31 Mood Grid Response

Further quantitative analysis was conducted using box and whisker charts (box plots) to provide a graphical interpretation of the data (Figure 32and Figure 33), central tendency, and variability of a dataset. To get the descriptive statistics with the consideration of individual preferences, the median and extreme numbers are included and marked separately so the data is not influenced by the outliners while makes it easier to identifying the abnormality. The spread of the data within these plots illustrates its variability, indicating how concentrated or dispersed the responses were.

The box plot for the Valence from mood grid reveals that the highest value recorded were in the IDL scenario, followed by DL and IDH scenarios. DH however, yielded the lowest Valence values across the participants. The correlated median values of four lighting scenarios were: IDL = 3, IDH = 2, DL = 2, and DH = 1. Particularly, the valence values in DL and IDL have the smaller range within the first and the third quartile, which suggest a more consistent positive feelings in the scenarios with low intensity for both direct and indirect lighting. For the IDH scenario, the data has a wider spread but with the higher value in average and median, which indicates a more split subjective feeling. While in DH, people had more negative feeling with a lower Valence value, in this light condition.

For Arousal, the box plot analysis, despite the presence of some outliers marked on the graphs, clearly indicated a significant positive correlation between light intensity and subjective arousal levels. Participants exposed to higher light intensity environments consistently reported correspondingly higher levels of arousal. (See Figure 32 and Figure 33)

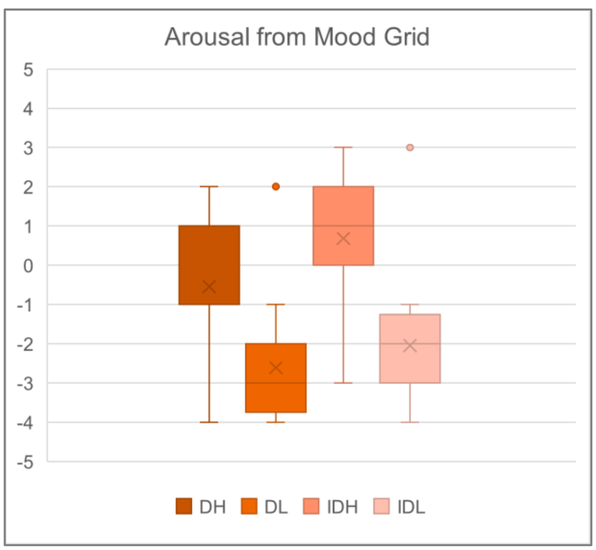


Figure 32 The box plot chart for the arousal from Mood Grid

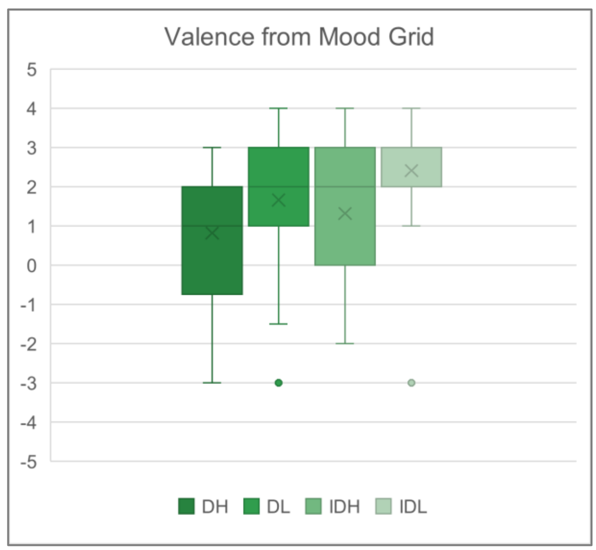


Figure 33 The box plot chart for the valence from Mood Grid

3.7.2.2. Mood Score in Four Lighting Scenario

The average scores and changes in Energy, Tiredness, Tension and Calmness across the four lighting scenarios were examined, calculated and analysed. The Activation-Deactivation Adjective Checklist (AD ACL) has been used to self-report measures developed by (Thayer, 1986), which assess transitory mood states along four subscales:

- Energetic score, or the General Activation (e.g., energetic, active).
- Tired score, or the General Deactivation (e.g., tired, drowsy).
- Tension score, or the High Activation (e.g., jittery, fearful).
- Calmness score or the Low Activation (e.g., calm, placid).

The total scores for each subscale are calculated by summing responses to the relevant adjectives, which applied with a 4-point Likert scale. The adjective rating of each respondent and further visualize in a chart (see Figure 34) and line graph (see Figure 35) to visualise the relationships between the four scores under four lighting scenarios.

Participant Number	active	drowsy	fearful	sleepy	lively	still	energetic	wide-awake	intense	calm	quiet	tired	vigorous	tense	at rest	wakeful	Energetic Score (4-16)	Tired Score (5-20)	Tension Score (3-12)	Calmness Score (4-16)
DH																				
3	3	1	1	1	4	3	3	3	1	4	3	1	1	1	3	4	11	10	3	13
4	4	1	3	1	3	2	3	3	3	1	2	2	2	3	1	3	12	10	9	6
5	3	1	3	1	2	4	2	3	2	1	1	1	3	4	1	3	10	9	9	7
6	2	3	1	3	2	2	1	3	1	3	3	3	2	2	3	3	7	15	4	11
7	3	2	1	2	3	1	2	3	1	3	4	2	2	1	2	3	10	12	3	10
8	1	1	1	1	1	3	1	3	1	3	4	3	1	1	3	1	4	9	3	13
9	3	1	3	1	3	1	3	3	2	3	2	1	1	1	2	4	10	10	6	8
10	2	2	1	1	2	2	2	2	1	2	2	1	1	1	1	3	7	9	3	7
11	3	2	1	2	3	4	2	3	2	3	3	2	2	1	4	4	10	13	4	14
12	1	3	1	2	1	3	1	1	1	3	3	1	1	1	3	1	4	8	3	12
13	3	1	3	1	3	1	3	3	4	1	1	1	3	3	1	3	12	9	10	4
14	2	1	1	1	3	3	1	1	3	4	1	3	2	1	3	3	8	9	5	11
15	1	3	1	4	1	4	1	1	1	3	3	4	1	2	3	1	4	13	4	13
16	3	2	2	1	3	3	1	2	1	2	2	3	1	2	1	3	8	11	5	8
17	1	4	1	4	1	4	1	1	1	4	4	4	1	2	4	3	4	16	4	16
18	1	4	1	4	1	4	1	1	1	4	4	4	1	3	1	1	4	14	5	13
19	2	2	2	2	2	2	3	3	3	2	2	3	2	3	2	3	9	13	8	8
21	3	1	1	3	2	4	3	3	1	4	4	1	3	1	3	3	11	11	3	15
22	2	4	1	4	1	3	2	2	1	3	4	4	1	1	3	2	6	16	3	13
23	1	3	1	3	1	3	1	2	1	1	3	3	1	3	1	2	4	13	5	8
Average																	7,75	11,5	4,95	10,5
DL																				
3	1	3	3	1	1	4	1	1	2	4	4	3	1	2	3	2	4	10	7	15
4	3	2	3	2	1	3	1	2	3	2	2	2	3	3	1	3	8	11	9	8
5	1	1	1	1	3	3	3	2	2	3	2	1	3	1	3	2	10	7	4	11
6	3	3	1	3	2	3	1	1	1	3	3	3	2	1	3	1	8	11	3	12
7	1	4	2	4	1	2	1	2	3	4	4	4	2	1	4	3	5	17	6	14
8	1	1	1	4	1	3	1	1	1	4	4	1	1	1	4	1	4	8	3	15
9	1	3	1	4	1	4	1	1	1	4	4	3	1	1	4	1	4	12	3	16
10	1	1	1	1	3	3	2	2	1	3	3	1	2	1	2	3	8	8	3	11
11	1	2	1	4	2	4	1	1	3	4	4	4	1	1	3	2	5	13	5	15
12	1	3	1	3	1	3	1	1	1	4	4	3	1	1	4	1	4	11	3	15
13	3	1	3	1	3	1	1	3	3	2	1	1	1	3	1	1	8	7	9	5
14	1	3	1	4	1	4	1	1	3	4	4	3	1	1	4	1	4	12	5	16
15	1	4	1	4	1	4	1	1	1	4	4	4	1	1	4	1	4	14	3	16
16	1	2	1	3	2	3	2	1	1	4	4	1	1	1	4	1	6	8	3	15
17	1	4	1	4	1	4	4	1	1	4	4	4	1	3	3	4	7	17	5	15
18	1	4	1	4	1	4	1	1	2	4	4	4	1	1	4	1	4	14	4	16
19	3	3	2	3	2	2	2	2	2	3	3	4	1	1	3	2	8	14	5	11
21	1	1	1	4	1	3	1	1	1	4	4	3	1	1	4	1	4	10	3	15
22	1	4	1	4	1	3	1	1	1	4	4	4	1	1	4	1	4	14	3	15
23	1	4	3	3	1	1	1	1	3	2	3	4	2	3	3	1	5	13	9	9
Average																	5,7	11,6	4,8	13,25
IDH																				
3	4	1	1	1	4	2	4	4	3	2	2	1	2	3	1	4	14	11	7	7
4	3	1	2	1	3	2	3	2	1	3	3	1	2	1	1	3	11	8	4	9
5	3	2	1	2	3	2	3	2	1	3	2	2	1	1	3	2	10	10	3	10
6	3	1	1	1	3	2	3	3	1	3	3	1	2	1	3	3	11	9	3	11
7	1	4	1	4	3	1	1	1	1	4	4	4	1	1	4	1	6	14	3	13
8	2	1	1	1	1	3	1	3	1	3	3	1	2	1	4	1	6	7	3	13
9	4	1	2	1	4	1	2	4	3	3	3	1	2	1	1	4	12	11	6	8
10	3	2	1	1	4	3	3	3	1	3	3	1	1	1	1	3	11	10	3	10
11	3	1	1	1	2	4	2	3	2	3	4	2	2	1	3	3	9	10	4	14
12	1	2	1	1	1	4	1	1	1	4	3	2	1	1	4	1	4	7	3	15
13	3	1	1	1	3	3	3	3	1	3	3	1	3	1	3	1	12	7	3	12
14	3	1	1	1	3	1	3	4	1	3	1	1	3	4	1	4	12	11	6	6
15	1	3	1	3	1	4	1	1	1	4	4	4	1	1	4	1	4	12	3	16
16	3	1	1	2	3	1	2	3	1	3	3	1	1	1	2	3	9	10	3	9
17	3	1	1	2	2	1	3	2	1	4	1	3	3	1	4	3	11	11	3	10
18	1	4	1	4	1	4	1	1	2	4	4	4	1	1	4	1	4	14	4	16
19	4	3	2	1	3	2	3	3	2	3	2	2	3	2	3	3	13	12	6	10
21	3	3	3	1	3	1	2	3	4	1	3	3	2	1	1	4	10	14	8	6
22	3	2	1	1	3	2	3	3	2	2	3	2	3	2	2	3	12	11	5	9
23	3	1	1	1	3	2	2	3	1	3	2	1	1	1	4	1	9	7	3	11
Average																	9,5	10,3	4,2	10,8
IDL																				
3	4	1	1	1	4	3	4	4	4	3	1	1	2	3	3	3	14	10	8	10
4	1	3	1	3	1	2	1	1	1	3	3	3	1	2	3	1	4	11	4	11
5	2	2	1	3	2	4	2	2	1	3	3	2	1	1	3	1	7	10	3	13
6	3	3	2	3	3	3	1	1	1	4	3	3	2	1	3	1	9	11	4	13
7	1	4	1	4	2	3	1	2	1	4	4	4	1	1	4	1	5	15	3	15
8	3	1	1	1	4	3	1	1	1	3	3	1	1	1	3	3	9	7	3	12
9	1	3	1	3	2	4	1	2	1	4	4	3	1	1	4	1	5	12	3	16
10	3	2	1	1	3	3	4	3	1	2	3	1	2	1	1	4	12	11	3	9
11	2	3	1	3	2	3	2	2	1	3	3	2	1	1	4	3	7	13	3	13
12	1	3	1	3	1	3	1	1	1	4	4	3	1	1	4	1	4	11	3	15
13	1	3	1	4	3	3	1	1	1	4	4	3	1	1	4	1	6	12	3	15
14	2	2	1	3	2	3	1	1	1	3	1	3	1	1	3	1	6	10	3	10
15	1	3	1	3	1	4	1	1	1	3	4	4	1	2	3	1	4	12	4	14
16	2	1	1	2	3	3	2	2	1	3	3	1	1	1	4	3	8	9	3	13
17	1	3	1	4	1	4	1	1	1	4	4	4	1	1	4	1	4	13	3	16
18	1	4	1	4	1	4	1	1	3	4	4	4	1	1	4	1	4	14	5	16
19	1	1	1	4	1	2	1	2	1	4	4	3	2	1	4	1	5	11	3	14
21	1	3	3	4	1	1	1	1	3	1	2	4	1	3	2	1	4	13	9	6
22	1	3	1	4	1	2	2	2	1	3	4	3	1	1	4	1	5	13	3	13
23	1	3	1	3	1	3	1	1	1	3	3	1	1	1	4	2	4	10	3	13
IDL Average																	6,3	11,4	3,8	12,9

Figure 34 The overview chart from AD ACL scores

The line graph (Figure 35) indicating the average mood scores from each scenario revealed a clear correspondence between General Activation (Energy) and Low Activation (Calmness) scores with the two light intensities.

Energetic score (General Activation) were comparative higher under the light scenarios with high intensity (DH = 7.75, IDH = 9.5) compared to the low intensity scenarios (DL = 5.7, IDL = 6.3). Calmness score (Low Activation) were relatively lower under the light scenarios with high intensity (DH = 10.5, IDH = 10.8) compared to the low intensity scenario (DL = 13.25, IDL = 12.9) In terms of tired and tension scores, there is no significant differences among the four lighting scenarios. (Tired score: DH = 11.5, DL = 11.6, IDH = 10.3, IDL = 11.4; Tension score: DH = 4.95, DL = 4.8, IDH = 4.2, IDL = 3.8)

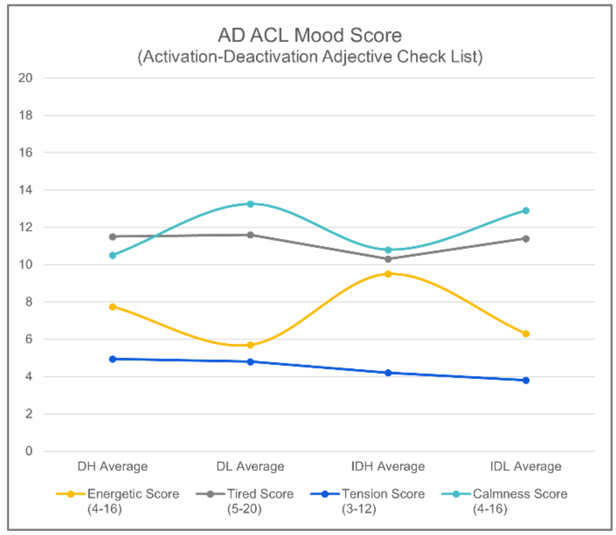


Figure 35 Activation- Deactivation Mood Score

The box plot chart below (see Figure 36) indicates the scores distribution, central tendency and variability of data for four mood scores under different lighting scenarios. As the conducted significant test (3.7.3. Significant Difference Test), the results showed the significant difference for energetic and calmness score within the four lighting scenarios, while there is no significant difference in terms of tired and tension score among different conditions. As for the normality test conducted before the parametric or non-parametric test, the energetic and tension scores did not have a normal distribution of the data due to some extreme values. According to the chart, there are outliners for the mentioned scores and the wider spread of the data. With this method, we can see the similar trends for the line graph of average mood scores, which is the correlation between general /low activation and high/ low light intensity. Additionally, under the scenario with high intensity, for the values in energetic scores of all participants, it showed that people have higher general activation with indirect light than direct light. Comparably, under the scenario with low light level, for the calmness scores of all, they shared the similar value (The average of Calmness score: DL – 13.25, IDL – 12.85) but the one with indirect light has a more concentrated spread among data than the one with direct light.

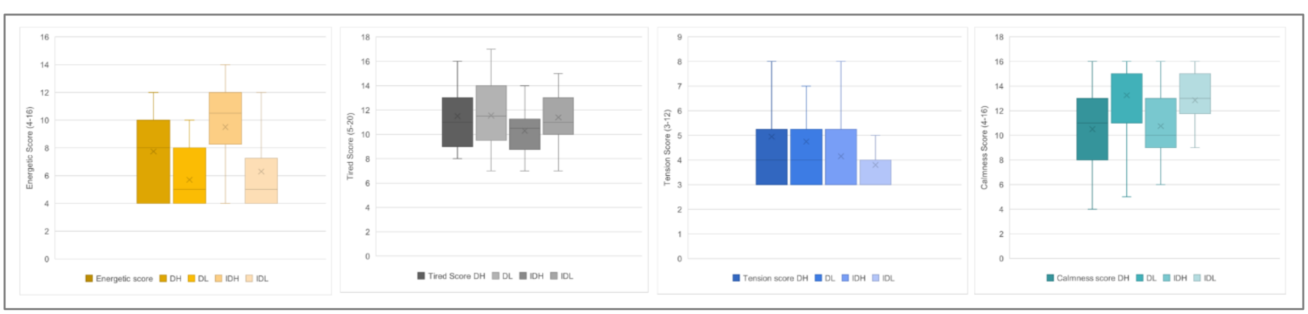


Figure 36 Activation- Deactivation mood score (2)

3.7.2.3. Semi-constructive Interview

The post-test interviews were analysed using a qualitative analysis approach to identify patterns in participants' subjective experiences of four different lighting scenarios: Direct light with High intensity (DH), Direct light with Low intensity (DL), Indirect light with High intensity (IDH), and Indirect light with Low intensity (IDL). The documented interview responses were reviewed systematically, and a combination of inductive and deductive organizing method was applied. Initially, the corresponding adjectives were extracted from repetitive descriptive vocabularies, emotional responses, and behavioural indicators related to each lighting condition. These descriptors were then categorized under the themes such as comfort, relaxation, attention, mood regulation, and spatial preference. Each quote was attributed to a participant using a consistent numerical identifier (e.g., P5), allowing for individual preferences to be marked across conditions.

Following initial method, the wordings were grouped by lighting scenario to evaluate which conditions were most frequently associated with positive or negative affective states. This process creates a comparative matrix to be developed, connecting the descriptors and contextual associations (e.g., reading, doing something, being alone) tied to each lighting setup. Additionally, the qualitative insights from the interview were also cross compared with quantitative mood scores from the AD ACL scale (Energetic, Tired, Tension, and Calmness) to examine consistency between self-reported mood and experiential descriptions. This mixed-method integration would provide a more comprehensive and deeper understanding of how the different lighting parameters influences relaxation and mood in residential spaces.

3.7.3. Significant Difference Test

The significant difference test was performed across all collected data to determine whether there were meaningful differences between the four scenarios. The average values for each scenario for each participant were calculated using Google Sheets, and these were linked to a Google Colab notebook that executed a script to run three different statistical tests

Shapiro-Wilk Normality Test

This test assesses whether a dataset is normally distributed, a common assumption for many statistical methods. It is more effective for small sample sizes like fewer than 50 data points. A normal distribution is when the data follows a bell-shaped curve. If the dataset fails this test, meaning that it doesn't have a normal distribution, then the ANOVA test does not work because it relies on a normal distribution. The normality of the data doesn't indicate if there is any significant difference only the distribution of measurements between scenarios follows that "bell-shaped" curve. If the calculated P-Value is below 0.05 it is set to be non-normal and if its above 0.05 its Normal. The normality test is used to determine the type of significant difference test to apply based on the data distribution (*Examining Normality: The Shapiro-Wilk Test - On Statistics*, 2024).

Friedman Test

The Friedman Test is a non-parametric statistical test that is used to detect differences across several different scenarios. It is often used when the same individual is exposed to different scenarios like this case with the different light scenarios.

Unlike parametric tests such as ANOVA, the Friedman Test does not assume a normal distribution, making it useful when the data fails the Shapiro-Wilk test. It ranks the values within each subject across the conditions and then analyses those ranks to determine whether the observed differences are likely due to chance (*Friedman Test Tutorial: Analyzing Repeated Measures Data*, 2025).

Repeated Measures ANOVA

This parametric test is used to compare the mean across several participants when exposed to different scenarios. Repeated Measures ANOVA assumes that the data is normally distributed and that the variances between the conditions are roughly equal (sphericity). When these assumptions are met, this test can detect subtle differences in means between conditions that might not be evident through simpler comparisons (*Repeated Measures ANOVA: Step-by-Step Guide*, 2025).

3.7.3.1. EEG

Arousal and valence levels were calculated for each participant within each of the four experimental lighting scenarios: Direct High (DH), Direct Low (DL), Indirect High (IDH), and Indirect Low (IDL). The average arousal and valence scores for each participant per scenario were systematically calculated and organized within a Google Spreadsheet. A Python script, executed in Google Colab, was linked to this spreadsheet to perform the statistical significance tests previously detailed (3.7.3. Significant Difference Test).

The overall results of these analyses, as illustrated in Figure 37, indicated no statistically significant differences in either arousal or valence levels among the four lighting scenarios. This finding held consistently, regardless of whether a moving average filter was applied to the data or which of the two arousal and valence calculation methodologies (Calculation (A) and Calculation (B)) were employed.

For Calculation (A) using Valence (A) and Arousal (A) explained in section 2.1.3. Arousal and 2.1.4. Valence using the moving average filter was needed to meet the assumption of normality. After filtering all values of Calculation (A) data passed the normality tests, this indicates that the moving average filtering process smoothed the data, leading to distributions consistent with normality.

Looking at the results without filtering, Calculation (B) for both Valence and Arousal provided the “cleanest” output, as its data was normally distributed across all conditions from the outset. Applying the moving average filter for Calculation (B) did have a minor impact on the results of either the P-value form the Normality test, Friedman test or the ANOVA test. For instance, for Valence (B) without filtering, the ANOVA test resulted in a P-value of “p=0.3159”, on the other hand with filtering it was “p=0.3150”, showing minimal change.

In contrast, Calculation (A) data was more reliant on the filtering process to achieve normal distributions. Filtering was therefore more pronounced for Calculation (A), not only in terms of meeting normality assumptions but also in the p-value result from the statistical tests. For Calculation (A), p-values from the Friedman test decreased with filtering, unfiltered Valence (A) resulted in “p=0.4202” compared with filtered the P value was “p=0.2232”.

ANOVA results on the other hand had the opposite effect where the results for Calculation (A) increase with filtering, Valence (A) unfiltered has a P value of “p=0.3309” increasing to “p=0.9829" with filtering.

		Without filtering															
		Valence (A)				Arousal (A)				Valence (B)				Arousal (B)			
		DH	DL	IDH	IDL	DH	DL	IDH	IDL	DH	DL	IDH	IDL	DH	DL	IDH	IDL
Normality test	Normality	N-N	N	N-N	N	N	N-N	N	N	N	N	N	N	N	N	N	N
	P-Value	0.00	0.22	0.04	0.10	0.48	0.00	0.30	0.34	0.96	0.82	0.98	0.39	0.33	0.59	0.93	0.52
Friedman test	P-Value	0.4202				0.5766				0.2177				0.9361			
Anova	P-Value	0.3309				0.2923				0.3159				0.9630			

		With Moving Average filter (12 values)															
		Valence (A)				Arousal (A)				Valence (B)				Arousal (B)			
		DH	DL	IDH	IDL	DH	DL	IDH	IDL	DH	DL	IDH	IDL	DH	DL	IDH	IDL
Normality test	Normality	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	P-Value	0.58	0.99	0.92	0.16	0.50	0.14	0.16	0.91	0.96	0.82	0.98	0.39	0.33	0.59	0.93	0.52
Friedman test	P-Value	0.2232				0.4010				0.2177				0.9361			
Anova	P-Value	0.9829				0.4215				0.3150				0.9629			

Normality test “N-N” is Non-Normal distribution and “N” is normal distribution.
P-Value for Normality test: results < 0.05 is significant different and are resulting in a Non-Normal distribution.
P-Value for Friedman test and Anova: results < 0.05 shows a significant different between scenarios.

Figure 37 Statistical Difference EEG

3.7.3.2. Mood Questionnaire

A series of significance tests was conducted to examine valence and arousal levels collected from the Mood Grid across the four distinct lighting scenarios: Direct High (DH), Direct Low (DL), Indirect High (IDH), and Indirect Low (IDL).

Valence, the normality test revealed that most conditions did not behave in the normal distribution, DH (p= 0.0314), DL (p= 0.0133), IDH (p= 0.0502), IDL (p= 0.0007), suggesting the use of non-parametric analysis. The Friedman test indicated a statistically significant difference in valence scores across lighting conditions, p = 0.0017. This finding was also supported by the repeated measures ANOVA, which also showed a significant effect of lighting on valence, p = 0.0189; however, due to normality failure, the Friedman result is more reliable because the Anova test assumes a normal distribution from the normality test. **Arousal**, the data from only one of the four lighting conditions, DH (p= 0.0599) met the normality test. The Friedman test again revealed a highly significant difference in arousal scores between scenarios, p < 0.0001, suggesting that lighting conditions had an influential impact on participants’ arousal levels.

As a results, both the valence and arousal data from the mood grid reveal the significant outcomes, which indicates the lighting scenarios in this study are giving the different effects to participate (see Figure 38). However, the frequent violation of normality assumptions suggests the potential presence of extreme high or low values influencing the data distributions.

		Mood Grid							
		Valence				Arousal			
		D-H	D-L	ID-H	ID-L	D-H	D-L	ID-H	ID-L
Normality test	Normality	N-N	N-N	N	N-N	N	N-N	N-N	N-N
	P-Value	0.0314	0.0133	0.0503	0.0007	0.0599	0.0021	0.0226	0.0013
Friedman test	P-Value	0.0017				0			
Anova	P-Value	0.0189				0			

For the normality test "N-N" is Non-Normal and "N" is Normal distribution.
P-Value need to be under 0.05 to be a significant difference.

Figure 38 The chart is the results of significant test for Valence and Arousal from mood grid in different lighting scenarios.

To determine if AD ACL mood scores exhibited meaningful difference within the different lighting conditions, significant tests has conducted separately for each of the four mood subscales: energetic, tired, tension and calmness score.

Out of the tests results, the energetic and calmness score indicated the significant difference within the four lighting scenarios, which means the scenarios in this study strongly affected participants' feelings of energy and calmness, while participants had the consistent mood in terms of tired and tension score among different light conditions (see Figure 39).

For the energetic scores in different lighting scenarios, out of the normality test, the p values of all scenarios are lower than 0.05, DH (p=0.0154), DL (p=0.0007), IDL (p=0.0235), IDH (p=0.0009). Since all the data are not normally distributed, suggesting that non-parametric tests are more appropriate for the category. In the Friedman Test (Non-parametric alternative to repeated-measures ANOVA), there is a significant difference between the groups ($p < 0.05$) in the repeated measures setting ($p = 0.0001$).

For the tired scores in different lighting scenarios, all groups pass the normality test ($p > 0.05$), DH (p= 0.0745), DL (p= 0.2977), IDH (p= 0.0746), IDL (p= 0.6561), which validates the data from parametric test, repeated measures ANOVA. Both the Friedman test ($p = 0.2162$) and repeated measures ANOVA (p= 0.0650) indicate that there is no significant difference in tiredness scores across the four lighting scenarios. This suggests that the reported tiredness levels of the majority of participants remained consistent across conditions

For the tension scores among the different scenarios, none of them are normally distributed ($p < 0.05$ in all cases): DH (p= 0.0009), DL (p= 0.0004), IDH (p= 0.0746), IDL (p= 0.6561). Subsequently, the non- parametric test, the Friedman test, shows no statistically significant difference in tension scores across the four scenarios ($p > 0.05$). It indicates pparticipants' tension levels remained statistically similar regardless of the scenario exposed.

For the calmness scores, 3 out of 4 are approximately normally distributed ($p > 0.05$): DH (p= 0.3362), DL (p= 0.0009), IDH (p= 0.4280), IDL (p= 0.0608), which suggests a clear and statistically significant difference in calmness scores across the four scenarios. Within the parametric and non-parametric tests, the Friedman test confirms the validity ($p = 0.0003$) and the ANOVA also supports the conclusion ($p = 0.0016$), though with concerns due to one non-normal group.

		AD ACL Mood Score															
		Energetic				Tired				Tension				Calmness			
		D-H	D-L	ID-H	ID-L	D-H	D-L	ID-H	ID-L	D-H	D-L	ID-H	ID-L	D-H	D-L	ID-H	ID-L
Normality test	Normality	N-N	N-N	N-N	N-N	N	N	N	N	N-N	N-N	N-N	N-N	N	N-N	N	N
	P-Value	0.0154	0.0007	0.0235	0.0009	0.0745	0.2977	0.0746	0.6561	0.0009	0.0004	0.0002	0.0000	0.3400	0.0009	0.4280	0.0608
Friedman test	P-Value	0.0001				0.2162				0.1434				0.0003			
Anova	P-Value	0				0.065				0.1829				0.0016			

For the normality test "N-N" is Non-Normal and "N" is Normal distribution.
P-Value need to be under 0.05 to be a significant difference.

Figure 39 The chart is the results of significant test for AD ACL mood scores in different lighting scenarios.

4. Results

4.1. EEG

The collected EEG data are from the four scenarios investigating the two light parameters. The aim is to identify potential differences in arousal and valence levels across the four lighting scenarios: Direct High intensity (DH), Direct Low intensity (DL), Indirect High intensity (IDH), and Indirect Low intensity (IDL). The post data poses included several steps of investigation of type of filtering, Valence, Arousal calculations and significant difference testing.

4.1.1. Filtering

Filtering represents the initial step in the data processing workflow prior to applying the different Valence and Arousal calculation methods. One of the main advantages of using high-pass and low-pass filters is their ability to eliminate data points that fall outside a predefined range, allowing for the direct removal of outliers or artifacts. However, this method also has a notable limitation: it removes data points entirely, thereby reducing the overall size of the dataset. In contrast, moving average filter does not eliminate data but instead smooths peeks by averaging values over a specified window as shown in Figure 26. This method of smoothening the fluctuations while preserving the overall structure of the data makes it more appropriate for this study. During the data processing phase, various filter ranges were tested to identify the optimal configuration. The final implementation utilized a moving average filter with a window size of 12 data points. Given that the EEG headset recorded at a frequency of 25 samples per second (see section 3.3.1. 8-channel Wearable EEG Headset), this corresponds to a filtering window of approximately 500 milliseconds. This duration was considered sufficient for smoothing short-term fluctuations while preserving relevant patterns in brain activity. which means the moving average filter is looking at a span of 500 milliseconds.

4.1.2. Calculation

The results from the two different types of EEG data calculations, as illustrated in Figure 27, reveal a notable inversion in outcome patterns between Calculation (A) and Calculation (B).

Calculation (A) shows that there is an increasing positive Valence from Direct High intensity to Indirect Low intensity. As seen in “Figure 28 Valence, Arousal comparison” the Direct light has an overall higher Valence compared to Indirect lighting. This pattern becomes more pronounced with the application of the moving average filter, which smooths the data and reveals a more gradual and consistent increase. However, the application of this filter also causes a reduction in the overall values, leading to a narrower range of variation in the results.

In terms of arousal, Calculation (A) shows that the Direct High scenario produces the highest arousal, with the remaining three scenarios following in descending order. Without filtering, arousal values under indirect lighting are slightly higher than under the Direct Low condition. However, after filtering, the differences between the scenarios are diminished, resulting in a clear downward trend in arousal levels. While filtering enhances data smoothness and reduces noise, it also compresses the variation between scenarios, thereby lowering the statistical distribution, as shown in “Figure 29 Statistical distribution between scenarios”.

In contrast, Calculation (B) exhibits a more balanced distribution across the scenarios, with a slight negative valence observed under indirect lighting conditions (see Figure 28). This trend aligns with expectations, as

Calculation (B) is mathematically the inverse of Calculation (A), comparing left-hemisphere activity to right-hemisphere activity (2.1. EEG).

Arousal follows the same inverted structure besides Direct Low scenario is consistently shown to have the lowest Arousal across the four scenarios. Calculation (B) is not influenced by the Moving average filter like calculation (A) that can conclude that the type of calculations produces a more stable results, with less sensitivity to signal fluctuations.

The primary finding from the EEG calculation is that the calculation (B) provides a greater range in the distribution of the results from the different scenarios. Scenario (B) has a distribution of “0,2” and “0,3” compared to calculation (A) that has a distribution of “0,02” and “0,06” (Figure 29).

4.1.3. Significant test

Normality tests (3.7.3. Significant Difference Test) were conducted on the EEG data to calculate if there were any significant difference between the different scenarios.

Calculation (A) was the moving average filter necessary to meet the assumption of normality. In contrast, data for Calculation (B) was found to be normally distributed across all conditions even without filtering. The application of the moving average filter had a minimal impact on the p-values from the Normality test, Friedman test, or ANOVA test for Calculation (B). For example, Valence (B) without filtering, the ANOVA test resulted in a p-value of p=0.3159, and with filtering, it was p=0.3150 (Figure 37 Statistical Difference EEG). For Calculation (A), filtering had a bigger effect on p-values from statistical tests, even though the final result didn’t change. For example, for Valence (A), the unfiltered Friedman test p-value was p=0.4202, which changed to p=0.2232 with filtering.

Despite the outcome from the two types of calculation and the bigger distribution of results from calculation (B) (Figure 29 Statistical distribution between scenarios) are the primary findings that there were no statistically significant differences in either arousal or valence between the four lighting scenarios. The overall statistical analyses from the Friedman Test and Repeated Measures ANOVA consistently showed no significant effect of the lighting scenarios and all had p- value results below 0.05 across the Arousal and Valence calculations.

4.2. Mood Evaluation Questionnaire

4.2.1. The subjective valence and arousal under four lighting scenarios

The subjective emotional responses from participants were measured using the Affect Grid, capturing the perceived arousal and valence under each lighting scenario. Analysis revealed a strong positive correlation between light intensity and arousal levels, with both high-intensity conditions (DH and IDH) producing significantly higher arousal levels compared to the scenarios with low-intensity. The result is consistent with prior findings that increased illuminance can elevate physiological and psychological activation, (2.2.3. Intensity) emphasizing the role of high intensity lighting in supporting states of activation.

As for the valence score, reflecting the pleasantness of the lighting experience, varied more distinctly across conditions. The IDL has the highest valence scores, followed by DL and IDH, with DH showing the lowest valence despite its energizing effect. This pattern suggests that while high illuminance supports arousal, it may reduce emotional comfort under some contexts, particularly when delivered through direct sources.

The reduced valence in IDH and DH could indicate subtle perceptual discomfort or cognitive overstimulation, which is consistent with (2.2.2. Direct and Indirect Lighting) who reported that overly intense lighting can negatively impact subjective well-being.

The overall findings align with research (2.2.1.1. Luminance) which highlights that low to moderate illuminance with indirect sources tends to be perceived as more comfortable and emotionally positive, which could support the psychological and physiological balance in the everyday environments.

4.2.2. The insights from AD ACL mood scores under four lighting scenarios

The data derived from the AD ACL assessments under four lighting scenarios, direct high-intensity (DH), direct low-intensity (DL), indirect high-intensity (IDH), and indirect low-intensity (IDL), which provide deeper insights into the relationship between lighting conditions and mood states. Among the four measured dimensions—energy, calmness, tension, and tiredness, the most notable finding was the inverse correlation between energetic and calmness scores, suggesting that increases in perceived energy are associated with reduced calmness. While tension and tiredness scores remained statistically consistent across lighting scenarios, suggesting these affective states are relatively stable and less influenced by lighting configuration in this context.

The subjective manifestations of energetic and tense arousal in interaction are descriptively labelled "tense-energy" and "tense-tiredness" or "calm-energy" and "calm-tiredness." Generally, calm-energy and calm-tiredness represent optimal mood states, while tense-energy and tense-tiredness are less optimal. The latter mood state is commonly seen in the modern society (Thayer, 1990).

However, a deeper examination of the energetic dimension, particularly in relation to the stable tension and tiredness scores, yields additional insights. Participants exposed to IDH reported higher energetic scores compared to those under DH, despite both settings exposing the light with high intensity. This implies that the indirect characteristics of light may enhance moderate alertness and vitality compared to the direct lighting, without increasing tension or fatigue. Similarly, a comparison between DL and IDL reveals that IDL not only preserves a sense of calm but also supports moderate energy levels. States of calm-energy would be associated with optimism, happiness, and physical well-being (Thayer, 1986). They are not only pleasurable, but energetic periods are associated with enhanced learning, thinking, and general intellectual activity (Thayer, 1990).

A combination of direct and indirect light could better align with the demands of modern working and living environments, which often require sustained concentration in low-stress conditions. These findings reveal the potential of indirect lighting, with different positive outcomes within the IDL and IDH. The IDH creates an energetic space without the trigger to tension and fatigue; the IDL creates a retrospective environment that also maintains subjective vitality while preserving a calm ambiance. These insights unfold a compelling basis for reevaluating lighting design in modern interior spaces.

4.3. Semi-constructive Interview

4.3.1. Subjective descriptions under four lighting scenarios

The qualitative data gathered from post-test interviews indicate a significant participant preference for indirect lighting with low intensity (IDL) as the most preferable in terms of the relaxation at home environment. This lighting condition was consistently described using adjectives such as “cozy,” “warm,” “comfortable,” “calm,” and “Hygge.” Several participants stated that IDL lighting created a restful and introspective atmosphere, with Participant 5 stating it was “creative and calm,” and Participant 19 emphasizing that it was “the best for creating a break from day-to-day life.” However, some participants noted that this setting was almost “too relaxing,” to the extent that it encouraged sleepiness (e.g., Participant 13).
In comparison, indirect lighting with high intensity (IDH) was also viewed positively but served a more functional purpose. Participants valued its brightness and clarity, especially for engaging in light tasks such as reading or cooking, while still maintaining a relaxed tone. Participant 15 characterized IDH as “the best balance… not too energizing and not too low,” indicating its suitability for transitional states between activity and rest at home environment.

Direct low-intensity lighting (DL) was often perceived as “homy,” “less distracting,” and tended to relax, although it lacked the warmth of atmosphere associated in the IDL. Participant 14, for instance, appreciated (DL) for its simplicity and noted it was “less distracting” compared to multiple light sources within the indirect light setting. On the contrary, direct high-intensity lighting (DH) received the most negative feedback across interviews. It was frequently described as “harsh,” “uncomfortable,” “stressful,” and even “annoyed,” with Participant 5 stating undoubtedly that they “hated DH a lot,” and Participant 11 noting it felt as though “something will happen,” indicating a sense of unease and restlessness. Overall, through analysing the interview, it reveals that participants associate relaxation with lighting that is dimmed, warm in colour temperature, and indirectly distributed, particularly in the form of reflected light source or "pool of lights ". These preferences suggest a significant alignment with principles found in human-centric lighting design aimed at enhancing visual and non-visual comfort in residential settings. The data validate that affective states measured from AD ACL correspond closely with subjective experiences, reinforcing the role of lighting qualities researched in this study, light intensity and directionality, in creating a relaxed residential lighting environment while supporting the psychological and physiological states for people.

Lighting Scenarios	Quotes from Participants under Four Lighting Scenarios	No. of Participants Preferred for Relaxation	Positive Descriptors	Negative Descriptors
DH	P5: "Hates DH a lot… time awareness seems longer." P11: "Second one (DH) is uncomfortable, like something will happen." P18: "Last one (DH) was a bit annoying."	0	—	harsh, uncomfortable, energizing, annoying
DL	P5: "DL and ID.L both good for a break from day-to-day life." P8: "DL most comfortable for relaxing after work." P8: "DL was the most comfortable and gave the best ability to relax after work." P9: "DL most relaxing." P13: "Second favorite after IDL." P14: "Liked DL most – less distracting." P16: "DL felt homy." P21: "DL was comforting, made him sleepy… gave a break from day-to-day."	7	comfortable, homy, calm, simple, subtle	less cozy than indirect, sleepy
IDH	P3: "Up and indirect light makes her positive and exploring." P7: "Liked IDH best… brightness made her relaxed but not sleepy." P10: "Liked IDL and IDH the most… didn't feel too intense." P15: "IDH was best for relaxation… not too energizing or too low." P18: "Preferred IDH to still be able to read or do something." P22: "Could like IDH because then he didn't fall asleep and was most comfortable." P23: "IDH was the best in terms of relaxation… gave a break from day-to-day life."	7	bright, balanced, interesting, safe, suitable for activity	sometime too active, distracted
IDL	P4: "IDL were the most comfortable… best to get a break from day-to-day light." P5: "IDL were my favorite one, it was creative and calm. I was able to let my mind wander." P6: "Dimmed indirect lights were the best… prefers to dim lighting to relax." P9: "DL the most to relax, then ID.L… prefers a bunch of small and warm light." P11: "IDL is favorite… turn the general light off, more dim toward the bed." P12: "4 > 1 (ID.L > DL)… very warm, as low as possible intensity." P13: "IDL was the most relaxing, almost too relaxing… could fall asleep." P16: "IDL the most in terms of being relaxed… intensity and color were pleasant." P17: "Liked IDL because it was cozy… lower lighting and warmer light when resting." P19: "IDL were the best to relax… most significant for creating the day-to-day relaxation."	11	cozy, warm, relaxing, hygge, calm, soft, homey, pleasant	too relaxing

Figure 40 The Overview Chart of Interview after Experiencing Different Lighting Scenarios

4.4. Comparison of Results

Comparing the results from the quantitative EEG data and qualitative self-reported measures provides a more comprehensive understanding of the physiological and psychological responses to the four different lighting scenarios.

Both Mood Grid and AD ACL the qualitative data show a similar trend where the scenarios (Direct-High and Indirect-High) are associated with higher Arousal and lower Valence scores compared to (Direct-Low and Indirect-Low) conditions are rated as more calming and pleasant, showing lower arousal and higher valence. This alignment is visualized in Figure 41 Comparison of Qualitative and quantitative results.

Among all qualitative results, the ADACL subscales for calmness and energy demonstrated statistically significant differences across lighting scenarios. Although the data failed the normality test, making ANOVA results less reliable, the Friedman test remained valid and yielded p-values of 0.0003 (calmness) and 0.0001 (energy). These findings indicate that participants experienced notable psychological shifts depending on lighting conditions, particularly in how energized or calm they felt.

The quantitative data from the two types of EEG Valence, Arousal calculations on the other hand have no significant difference between the four light scenarios regardless of the type of calculations. Compared to qualitative data, calculation(A) has more similar trends to the results from the Mood gid and AD ACL. For instance, Direct-High consistently shows high arousal across Mood Grid, ADACL, and EEG calculation (A). Similarly, Direct-Low and Indirect-Low display lower arousal in both qualitative and EEG Calculation (A) data.

For the Valence Direct-high, Direct-low and Indirect-low all show partial alignment across the three results in an ascending order. However, Indirect-High presents a deviation. While it shows higher arousal in the qualitative responses, it records low valence and arousal in EEG Calculation (A), highlighting a possible disconnect between perceived and neurological responses for this condition.

Calculation (B) has a bigger distribution between the different light scenarios (Figure 29), regardless does it not reveal any significant difference between light scenarios. Compared with the qualitative results has the scenario Indirect-low the highest Arousal and lowest Valence that are conflicting with the other results.

In summary, while qualitative measures captured perceptible differences in participants' emotional states under various lighting conditions, the EEG-based calculations in particular Calculation (B)were less sensitive to these distinctions. Calculation (A) provides closer alignment with the self-reported data, though still without statistical significance. These findings emphasize the complexity of correlating subjective emotional perception with physiological brain activity.

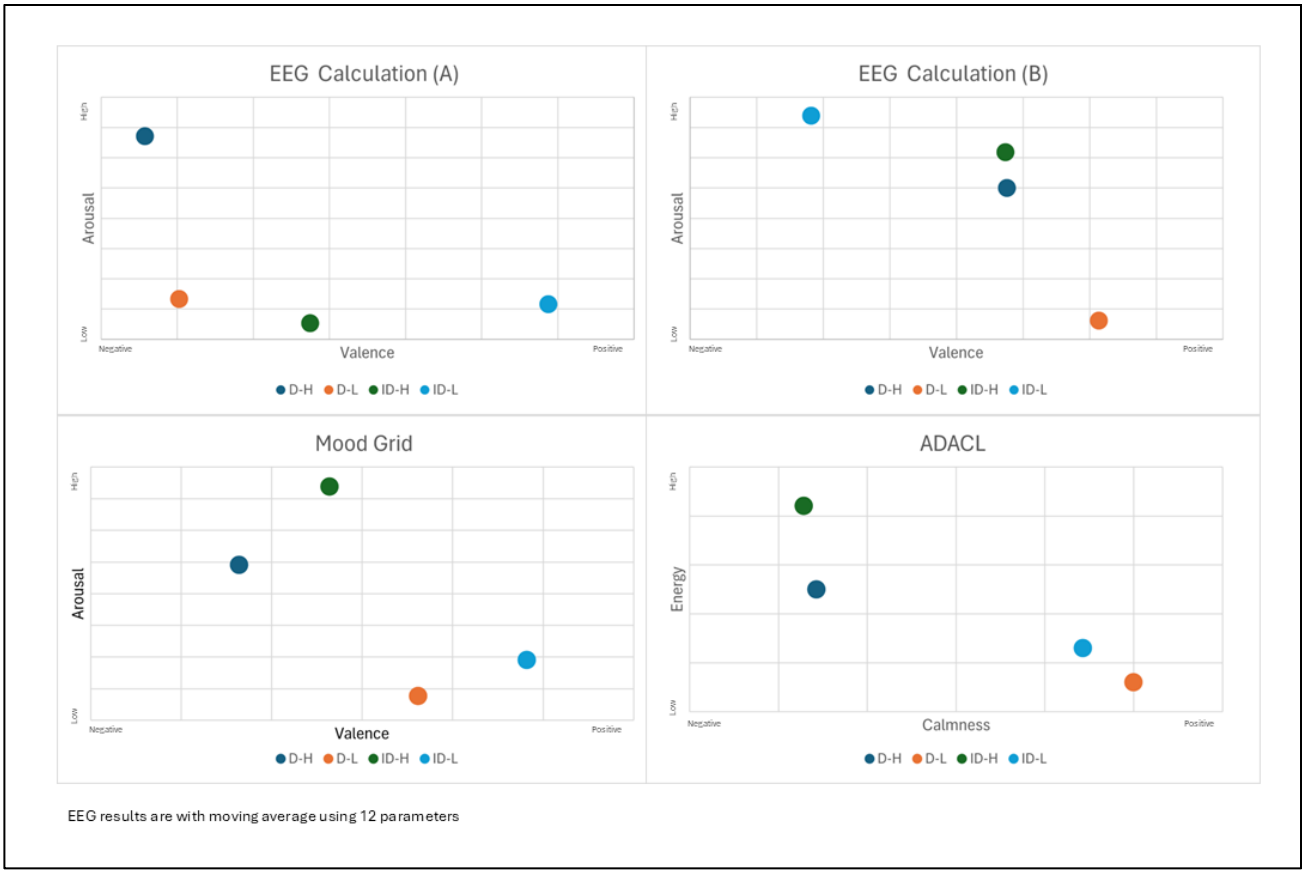


Figure 41 Comparison of Qualitative and quantitative results

5. Discussion

The aim of this study is to investigate "How does intensity and luminance from direct/ indirect light sources influences the physiological, psychological response in the context of relaxation and enhances emotional well-being in home environment." (1.2.1. Research Question). A mixed method approach is used to investigate physiological and psychological response using data from Electroencephalogram (EEG) recordings with data from mood evaluation questionnaires (Affect Grid and Activation-Deactivation Adjective Check List- AD ACL) and qualitative response from semi constructive interviews. The collected data in combination with literature will provide a bases for a "White Paper" with lighting guidelines to help consumers in creating a restorative environment.

5.1. Testing Scenario

The experiment conducted at the Muuto Showroom provided an optimal setting for the test, providing a controlled and home-like environment. It gave access to light fixtures representative of a wide consumer market, and it was in the center of Copenhagen, making it a professional and easy to access location for testing. A notable downside was its operation as an active showroom, that meant that the space needed to be in its original state during the day when customers were visiting the showroom.

That meant we needed to set up and take down the fixtures and curtains each day for testing. After completing all four lighting scenarios and the corresponding EEG recordings, participants were asked a series of questions regarding their overall experience, including their mood, emotional responses, and lighting preferences under each condition. To account for individual variability, factors such as each participant's health status, sleep quality, and recent lifestyle habits were documented and preserved as reference data for potential use in the analysis.

3.4. Participation of Muuto

A collaboration with Muuto was established for the practical experiment phase of this thesis. Muuto provided access to their showroom facilities and their available lighting fixtures, which served as the environmental setting for the testing.

Muuto is a Danish furniture company that is rooted in Scandinavian design traditions. Their focus is honest design that stimulate the senses and evoke feelings by a simple and familiar design.

"Our interiors are landscapes for authentic and analogue experiences. Our homes are filled with objects that stimulate the senses. Colores that evoke memories and emotions. Materials that trigger feelings. Shapes that tap into our subconscious. Objects influence our impression of space and how we feel when in the presence of them." (*Muuto - Our Story*, 2025) . Muuto's approach of how object and lighting are influencing our emotions and wellbeing are well aligned with the aim of this research.

The experimental design was developed independently and Muuto had no interference in the formulation of the research question, the design of the experimental methodology, the selection of the lighting fixtures or the analysis or interpretation of the data.

The collaboration with Muuto was based on the aligned objective to create a home environment that facilitates a restorative space and benefit both parties in creating the awareness of the visual and non-visual effects in the residential context.

3.5. Test Setting).

Before each testing session, spectrometer measurements were taken to ensure the consistency of the testing environment across different days (3.6. Test Procedure). This daily setup made a small variance between each scenario and potentially has a small influence on the results. While the central city location of the testing site offered distinct advantages in terms of participant accessibility, it also presented some unforeseen challenges. A clock tower located close by were each hour ringing that were more noticeable than foreseen, this and general noise from the street was something we didn't fully account for in the design, which may also have had a subtle influence on the physiological readings and the participants' overall ability to relax.

Testing sessions were conducted from March 24th to April 3rd, between 18:00 and 21:00. This timeframe was chosen to simulate, as closely as possible, a realistic scenario of being at home after work and to maximize conditions of natural darkness. One factor not accounted for was the change from wintertime to summertime that happened the 30 of march. This meant that the time was moved one hour earlier making it lighter than the previous days. Although the internal testing environment remained unchanged, variations in participants' prior daylight exposure due to this temporal shift could have potentially affected their overall energy levels and wakefulness.

A limitation of the four testing scenarios is the benchmarks established for light intensity. The intensity was measured and applied to the scenarios with a high intensity of 25 melanopic lux and low intensity of 4 melanopic lux (3.6. Test Procedure). These benchmarks were adopted due to the inherent limitations of the consumer-grade fixtures utilized.

The fixtures applied could not reach a higher intensity to create the same benchmarks for the Indirect lighting scenarios to achieve a higher M-EDI of 25Lux without necessitating the placement of an unrealistic number of fixtures within the testing location. For the Indirect lighting scenarios six fixtures were selected, this quantity was considered a realistic number and had a distribution and placement that would mimic a living room while reaching an M-EDI of 25 Lux. While a higher M-EDI benchmark might have potentially elicited a more pronounced difference in physiological and psychological responses, this could not have been achieved without either replacing the indoor consumer products with professional-grade fixtures possessing a higher lumen output or increasing the number of fixtures to an extent that would be impractical for the simulated environment.

5.2. Hypothesis 1

The impact of Light intensity stated in 1.2.2. Hypothesis 1

Low <u>intensity</u> in the space would keep the arousal low, increase the positive valence and support the restorative environment.

Intensity has a big influence on the perception of the space and regulation of circadian rhythm. Existing literature is supporting that the intensity is crucial to control the internal clock in terms of the wake sleep cycle (2.2.3. Intensity). Several papers also utilize both quantitative and qualitative data to measure the light influence on the circadian rhythm and it is a well-supported approach (2.2.1. Visual Element of Light).

The physiological evidence collected with the EEG did not result in any statistically significant differences in arousal or valence when comparing low-intensity scenarios, Direct-Low (DL), Indirect-Low (IDL), with high-intensity scenarios, Direct-High (DH), Indirect-High (IDH). While Calculation (A) for EEG indicates a trend towards lower arousal in DL and IDL conditions compared to DH, and a general increase in positive Valence towards IDL scenarios, these differences did not reach the threshold for statistical significance with p-values from both Friedman and ANOVA tests being greater than 0.05. Strictly considering the EEG measurements with the applied calculations and data processing methods, the differences are not pronounced enough to support the hypothesis. For calculation (A) there are not enough differences in the results to give a clear statement, and this can be a lack of the calculation itself. Compared to Calculation (B), which has a higher distribution of the results show that utilizing different types of Valence and Arousal calculations would potentially be beneficial to have better and more accurate results. Notably, Calculation (B) produced an opposite effect on Valence compared to Calculation (A). This was anticipated, given that Calculation (B) compares the right hemisphere to the left hemisphere of the brain, whereas Calculation (A) compared the left hemisphere to the right (2.1.4. Valence Calculation). The results from calculation (B) conflict with the results from the psychological evidence, Indirect-Low has a negative Valence and a high Arousal which is the opposite from Calculation (A). A similar study "The effect on emotions and brain activity by the direct/indirect lighting in the residential " (Shin *et al.*, 2015)investigated the influence of direct /indirect lighting on emotions. They used paired t-tests to investigate subjective feelings with the measurement from the EEG but resulted in no significant difference and that is why a simpler and different approach was selected.

The paper did not find any significant difference between the two scenarios tested but an increased Valence were observed from the EEG in the scenario utilising a mix of Direct/Indirect lighting compared to only direct light that had a lower Valence. Arousal on the other hand did not have any difference between the two conditions. These results are aligned with the results from this thesis. Valence is in in both cases increasing from direct to indirect lighting and Arousal are not with a big different between scenarios (Shin *et al.*, 2015).

The psychological evidence, from the questionnaires and interviews, supports certain aspects of Hypothesis 1. Activation-Deactivation Adjective Check List (AD ACL) results illustrate that low intensity lighting significantly influences to higher "Calmness Scores" (Friedman Test, p=0.0003). Both the Direct Low intensity and Indirect Low intensity, lighting scenarios, resulted in higher calmness scores when compared to their high-intensity counterparts. Furthermore, high-intensity scenarios were linked to higher "Energetic Scores" (Friedman Test, p=0.0001). This finding indicates that reducing light intensity led to a decrease in 'Energetic Scores', a dimension which can be considered comparable to lower arousal (3.7.3. Significant Difference Test).

The interviews collected provided deeper insight into the participants' experience. The qualitative data supports the "restorative environment" statement of the hypothesis. Participants frequently described low-intensity scenarios, like using terms with restoration and positive effect, such as "cozy," "warm," "relaxing," and "calm". The indirect low intensity scenario, which combined low intensity with indirect light, was preferred for relaxation. For example, Participant 19 emphasized it was "the best for creating a break from day-to-day life", directly indicating a restorative quality. Even DL, while less favored than IDL, was described as "homy" and "less distracting," and helped participants "relax after work".

In summary, concerning Hypothesis 1, the psychological evidence clearly supported the statement that low light intensity would foster a restorative environment. The combination with the interviews and mood evaluation questionnaires data supports that Low intensity was associated with increased calmness and decreasing energy score that was perceived as a restorative environment. EEG data from Calculation (A) indicates that the Arousal was decreasing with a low intensity especially considering the direct lighting. However, since the EEG data did not demonstrate any statistically significant differences between the conditions, definitive conclusions cannot be solely based on these physiological results. Since the EEG data didn't show any significant difference can't any conclusion be based on those results.

5.3. Hypothesis 2

Hypothesis 2 involves the directionality of the light and aims to investigate if direct/indirect light has any influence on the ability to relax and create a restorative environment 1.2.3 Hypothesis 2.

The luminance from Indirect light in the space would keep the arousal low, increase the positive valence and support the restorative environment.

Like Hypothesis 1, Hypothesis 2 found stronger support from psychological data than from physiological measures.

The EEG data did not show statistically significant differences in Arousal or Valence between the two light directionality scenarios, both Indirect-Low (IDL) and Indirect-High (IDL) showed a similar result. Trends in EEG Calculation (A) suggested that IDL had the most positive Valence and low Arousal among the scenarios, and Calculation (B) showed IDH and IDL with generally lower arousal than DH, beside in calculation (B) IDL had higher arousal than DL. However, these were not statistically robust. Therefore, the EEG results alone did not provide clear support for Hypothesis 2's statement that indirect light would keep arousal low and increase positive valence at a physiological level.

Psychological Evidence with Questionnaires and Interviews provided substantial support. The AD ACL, while direct statistical comparison between the two types of light conditions was not explicitly performed in the results section, are comparisons between individual scenarios supporting some strong results. For instance, comparing IDH with DH (both high intensity), IDH was often described more positively in interviews as "bright, balanced, indirect, safe, suitable for activity", whereas DH was "harsh, uncomfortable". This points to a more positive psychological response to indirect light even at higher intensities. The finding which stands out was the strong preference for the IDL (Indirect Low intensity) scenario in the interviews. This scenario was consistently rated as the most "cozy," "warm," "relaxing," "hygge," and "pleasant", clearly indicating that the combination of indirect light and low intensity was perceived as highly restorative and positive. Participants felt that indirect lighting created a softer, more diffuse, and visually comfortable environment. Participant 22 noted that IDH was "the most comfortable" and "gave a break from day-to-day life", suggesting restorative qualities even in a higher intensity indirect setting. The AD ACL results also showed that at high intensity, IDH led to higher energetic scores than DH (9.5 vs 7.75) but also slightly higher calmness scores (10.8 vs 10.5). However, at low intensity, IDL had comparable calmness to DL (12.9 vs 13.25) but was qualitatively far more preferred.

To summarize Hypothesis 2 like the fist hypothesis, did the EEG data do not offer a significant difference to support the statement that Indirect light leading to lower Arousal and increasing a positive Valence. Psychological data however, particularly from the interviews, strongly supported the idea that indirect lighting, especially when combined with low intensity (IDL), creates a highly restorative and emotionally positive environment. Participants' subjective experience clearly favored indirect over direct light for comfort and relaxation. AD ACL are also showing a distinct difference in higher Valence for the scenarios with indirect lighting compared to Direct lighting and an overall decreasing Arousal from Direct lighting to indirect lighting.

5.4. Research Question

To answer the Research Question:

How does intensity and luminance from direct/ indirect light sources influences the physiological, psychological response in the context of relaxation and enhances emotional well-being in home environment.

This study reveals a significant impact, particularly on the psychological dimension. The findings demonstrate that both light intensity and directionality strongly influence psychological responses related to relaxation and emotional well-being. Low intensity and indirect lighting, especially in combination (IDL), were consistently associated with increased feelings of calmness, comfort, and restrictiveness by participants. Conversely, high intensity and direct lighting (DH) were perceived negatively, inducing feelings of discomfort and stress. This aligns with substantial literature suggesting that softer, dimmer, and indirect lighting is preferred for evening relaxation and can contribute to a more positive affective state (Webler *et al.*, 2019b; Houser and Esposito, 2021b). The AD ACL results showing significant changes in 'Energetic' and 'Calmness' scores based on these lighting variations provide quantitative backing to these subjective experiences.

The physiological impact, as measured by the 8-channel EEG and the specific valence-arousal models employed, was less clear. The lack of statistically significant EEG findings suggests that the chosen lighting manipulations, within the 3-minute exposure and with the current EEG analysis method, did not elicit sufficiently changes in the measured brainwave patterns related to arousal and valence. This does not necessarily mean there was no physiological effect, but rather that the effects were not significant enough with the employed methodology. It is possible that more prolonged exposure, more targeted electrode placement and using a different type of Arousal, Valence calculation with potentially utilizing machine learning to detect more accurate values, might be needed to capture subtle physiological shifts. As noted in 1. 1.Introduction is "the transition between daily activities and bedtime represents an important window for mental restoration" that provide hormonal changes like melatonin production; EEG primarily captures electrical brain activity, which is only one factor of the overall physiological response to light.

The Interplay of Intensity and Direction most distinct psychological outcomes were observed in the IDL scenario, suggesting an interaction effect where the benefits of low intensity are amplified by indirect distribution. This combination appears optimal for creating an environment perceived as relaxing and emotionally supportive. The results also show that the intensity of the light had a bigger influence on the participants when it was direct. Direct High several participants were feeling “tens” and it gave the feeling like something would happen, when the intensity was turned down to low intensity the feeling changed to be relaxing. This is also supported by the AD ACL where the energy score is declining from high to low intensity and the calmness score is increasing from high to low intensity.

A factor is that the individual light scenarios tested in this paper are not a realistic representation of the average home where there is one single type of lighting. Typically lighting settings comprise of a dynamic interplay between both direct lighting and indirect lighting (2.2.1. Visual Element of Light). These two modes of illumination, and their combination, profoundly influence how individuals perceive an environment; for an optimal experience, a blend is often essential. Elements such as "focal glow," "ambient luminescence," and the "play of brilliants" are integral to creating a home environment that supports restorative experiences. To effectively achieve these qualities, a strategic combination of direct and indirect lighting is deemed necessary (Kelly, 1952).

6. Limitations and future research

The limitations previously discussed in section 5. Discussion about the Benchmarks, outside influence, sample size, EEG electrode placement, and Valenc/Arousal calculations are all factors that can be improved and revised. The lack of statistically significant EEG findings points to areas for methodological refinement in future research.

Future studies should aim to:

1. Conduct studies in real-world residential settings over extended durations to capture more ecologically valid data and to assess impacts on aspects like sleep quality and longer-term mood. Or increase the duration and participant list of a lab-oriented study, still applying a home like environment.

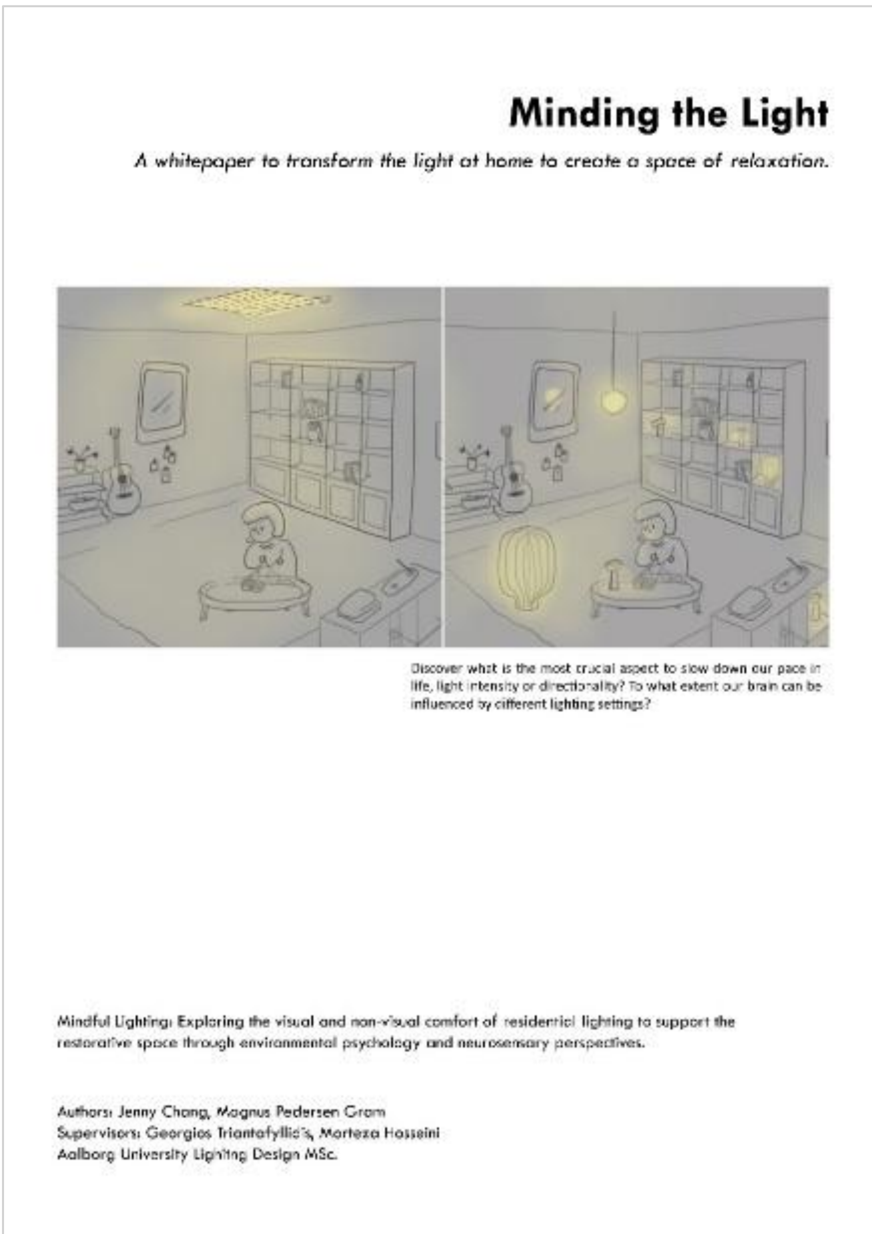
2. A more controlled environment where outside factors like noys and temperature can be controlled and measured and keep the placements and light scenarios to be exact the same for each day of testing.

3. More research and investigation into Valence and Arousal calculation models. The use of machine learning can be a method to increase accuracy and increase the distribution of results from the scenarios to result in a significant difference.

4. Applying a relaxing task in the testing scenario can potentially improve the relaxation to support mind wandering and prevent participants focusing on undone tasks.

7. Design Proposal

The design proposal is designed and presented as a white paper through a general knowledge regarding the light at home, summarized research results and the recommendations of light settings in the residential spaces. The white paper was organized in the informative order with five categories: the influence of lighting to the overall well-being in the modern society, the introduction of crucial lighting parameters at home, the comparison of the arousal and valence data objectively and subjectively, the insights from the questionnaires and interviews, finally the overall lighting recommendations for different levels of intensity and directionality considered the types of daily tasks at home.



Minding the Light

A whitepaper to transform the light at home to create a space of relaxation.

Discover what is the most crucial aspect to slow down our pace in life, light intensity or directionality? To what extent our brain can be influenced by different lighting settings?

Mindful Lighting: Exploring the visual and non-visual comfort of residential lighting to support the restorative space through environmental psychology and neurosensory perspectives.

Authors: Jenny Chang, Magnus Pedersen Gram
Supervisors: Georgios Triantafyllidis, Morteza Hosseini
Aalborg University Lighting Design MSc.

Figure 42 The front page of white paper

Mind the Light- A whitepaper to transform your light at home.

Lighting Design Master Thesis

How modern lifestyle and lighting influenced the human well-being?

The evolution of technology has changed the way we connect to our professional and personal life. Accordingly, the amount of time we spent indoors has increased, and especially the activities on the screen of digital devices, which unexpectedly allow the cognitive and sensory stimulation to occupy our everyday life. This information age is causing the rising demands from both professional and social responsibilities, forming an environment where stress and mental fatigue are frequently experienced in modern society. The transition between daily chores and slow-paced activities before bedtime is a crucial period for mental restoration.

In the evening hours, melatonin in the human body—a hormone that serves as a cue for the biological clock and supports sleep for the brain—should not be suppressed by any sort of stimulation, such as higher light levels (Zisapel, 2018).

However, most of the living patterns in modern society contradict the natural transition. When the daily routines have not aligned with the biological clock for a long period, the circadian rhythm would have consequences beyond the momentary discomfort but potentially impact the restore quality for the brain, which may increase the long-term stress levels and has a negative impact on the overall well-being. (Houser and Esposito, 2021a).

Lighting is a big contributor in terms of visual appreciation, sense of direction, and how we perceive the space. Apart from the visual effects, it has also an evident influence on the non-visual aspects, including physiological res-actions, biological signals to the brain and the circadian rhythm in human body.

With the problems and potentials addressed above, an optimal lighting design would play an important role in our lives and have the ability to support an overall well-being psychologically and physiologically.

What are the light qualities in residential space?

CCT (Corelated Color Temperature)

CCT defines the colour appearance of a white LED, which has the unit in Kelvin; a warm light is around 3000K, cool white at around 4000K, and daylight at around 6500K.

CRI (Color Rendering Index)

CRI is a measurement of how natural colors render under an artificial light source when compared with unlight. High CRI lighting renders complete tones across the full-color spectrum. The index of 100 indicating that colors of objects appear the same as they would under natural sunlight.

Intensity

Light intensity, also referred to as light level, is one of the most crucial parameters in spatial context. Higher light levels can stimulate alertness and support activities that require attention, while lower levels can support relaxation or create a sense of intimacy. It has also an impact on the human biological clock, mood, and cognitive performance.

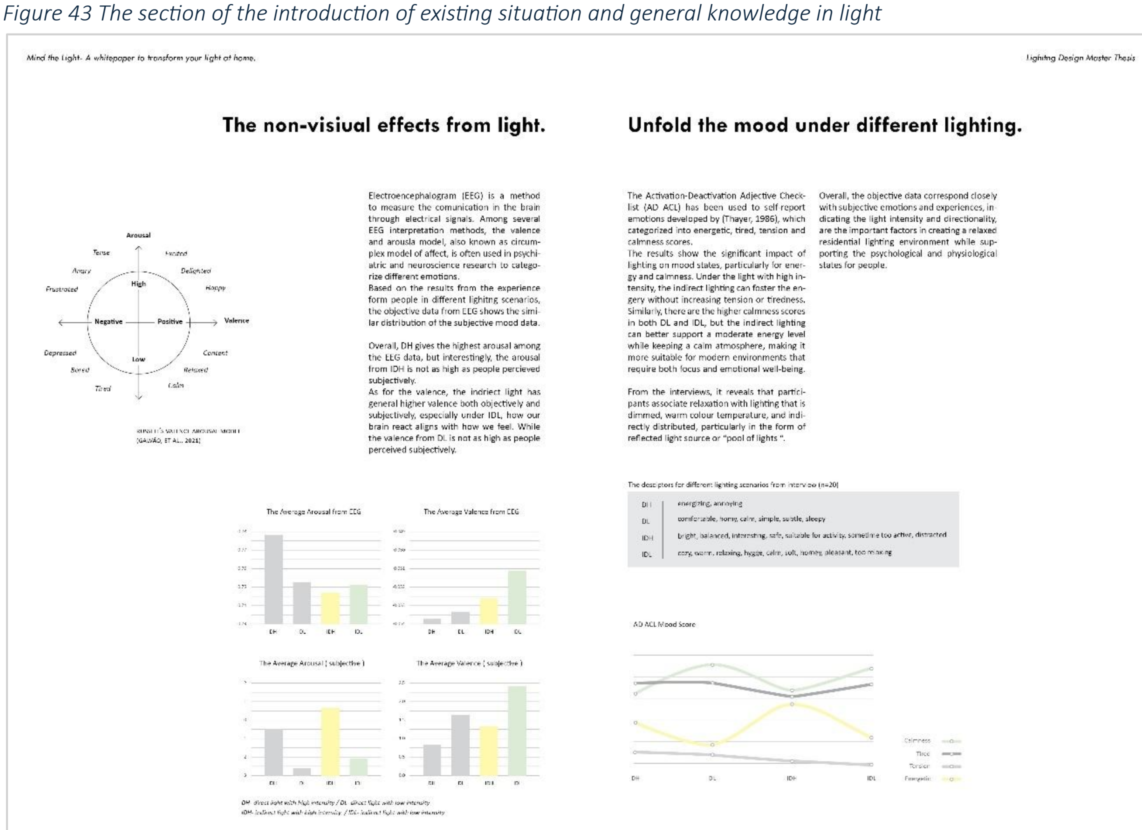
Directionality

The directionality of light can be categorized in three: up, down or multidirectional, and the application on surface as direct or indirect. (Descottes and Ramos, 2013) With different combinations, it would change the impression of the space and stimulate emotions. For example, a direct diffuse downlight would illuminate the area of floor, grounding the visitors in the space with a sense of stability.

M-EDI (Melanopic Equivalent Daylight Illuminance)

M-EDI is an index to measure how strong the light source stimulates the non-visual system in the body. It is dependent on the intensity of ight and its correlated colour temperature (CCT). M-EDI should be over 10 Lux to raise the alertness and energy in the offices or schools. (Zisapel, 2018; Houser and Esposito, 2021a; Brown et al., 2022)

Figure 43 The section of the introduction of existing situation and general knowledge in light



Mind the Light- A whitepaper to transform your light at home.

Lighting Design Master Thesis

The non-visiual effects from light.

Electroencephalogram (EEG) is a method to measure the comunication in the brain through electrical signals. Among several EEG interpretation methods, the valence and arousla model, also known as circumplex model of affect, is often used in psychiatric and neuroscience research to categorize different emotions.

Based on the results from the experience form people in different lighitng scenarios, the objective data from EEG shows the similar distribution of the subjective mood data.

Overall, DH gives the highest arousal among the EEG data, but interestingly, the arousal from IDH is not as high as people percieved subjectively.

As for the valence, the indriect light has general higher valence both objectively and subjectively, especially under IDL, how our brain react aligns with how we feel. While the valence from DL is not as high as people perceived subjectively.

DH- direct light with high intensity / DL- direct light with low intensity
IDH- indirect light with high intensity / IDL- indirect light with low intensity

Unfold the mood under different lighting.

The Activation-Deactivation Adjective Checklist (AD ACL) has been used to self report emotions developed by (Thayer, 1986), which categorized into energetic, tired, tension and calmness scores.

The results show the significant impact of lighting on mood states, particularly for energy and calmness. Under the light with high intensity, the indirect lighting can foster the engery without increasing tension or tiredness. Similarly, there are the higher calmness scores in both DL and IDL, but the indirect lighting can better support a moderate energy level while keeping a calm atmosphere, making it more suitable for modern environments that require both focus and emotional well-being.

From the interviews, it reveals that participants associate relaxation with lighting that is dimmed, warm colour temperature, and indirectly distributed, particularly in the form of reflected light source or "pool of lights ".

Overall, the objective data correspond closely with subjective emotions and experiences, indicating the light intensity and directionality, are the important factors in creating a relaxed residential lighting environment while supporting the psychological and physiological states for people.

The desciptors for different lighting scenarios from interview (n=20)

DH	energizing, annoying
DL	comfortable, homy, calm, simple, subtle, sleepy
IDH	bright, balanced, interesting, safe, suitable for activity, sometime too active, distracted
IDL	cozy, warm, relaxing, hygge, calm, soft, homey, pleasant, too relaxing

Figure 44 The section of the results from the EEG, questionnaire and interview

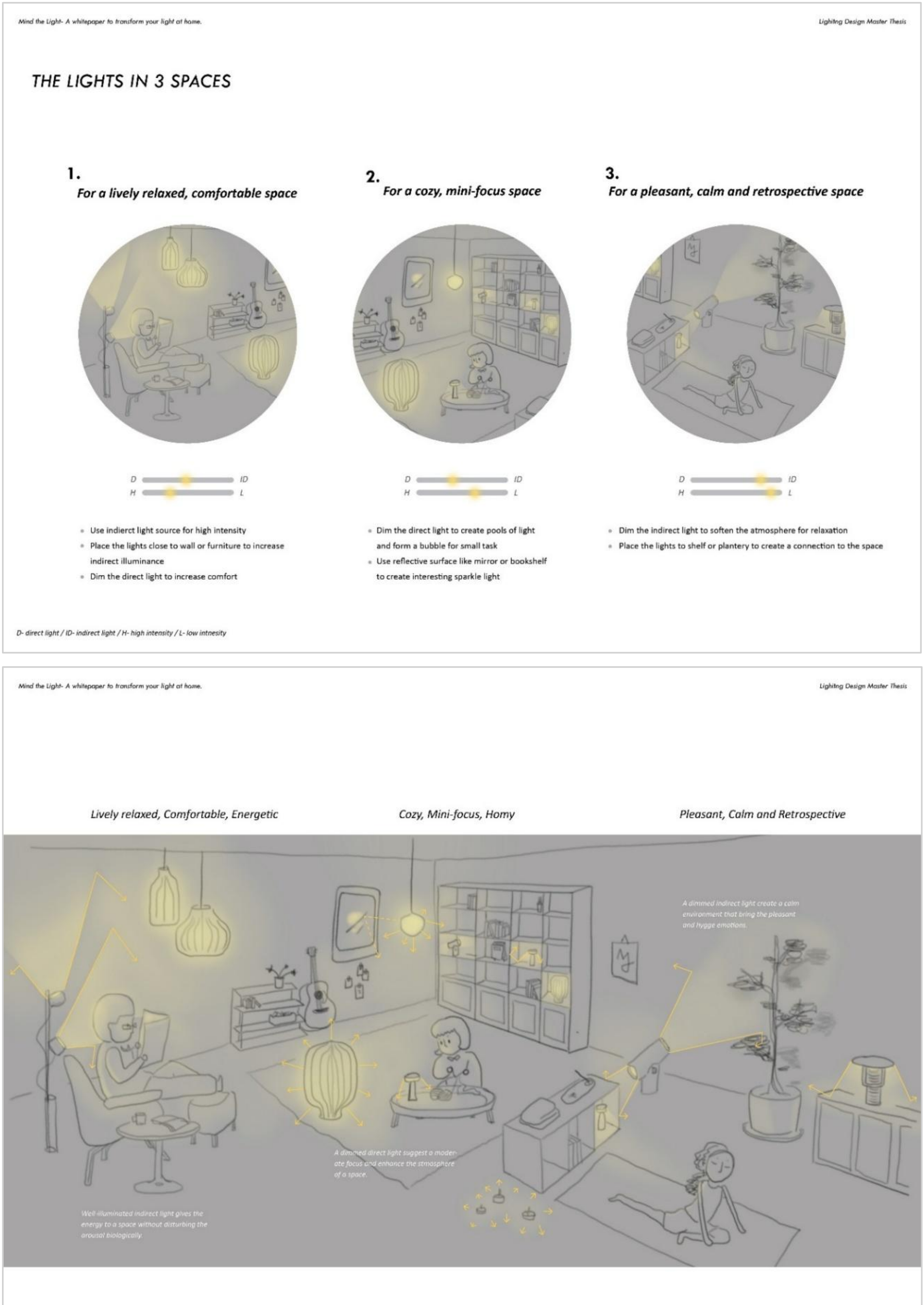


Figure 45 The parameters and insights for lighting recommendation at home

8. Conclusion

In conclusion, does this study demonstrate that light intensity and directionality significantly influence psychological perceptions of relaxation and emotional well-being in a simulated home environment. The qualitative results show a significant difference between the scenarios. The directionality of the light has a big impact on how much the intensity of the light is influencing the physiological response. With indirect light, the intensity can be higher without suppressing the melatonin response while maintaining a relaxed and comforting environment. Overall, high intensity is less preferable for a calm and restorative environment. Direct light is resulting in a higher arousal and lower valence associated with "Exited" and "Tense" feelings that are preferable for tasks and not a relaxed environment. Hypothesis 1 (regarding low intensity) and Hypothesis 2 (regarding indirect light) found considerable support from subjective questionnaires and qualitative interview data, which indicated that these conditions promote calmness, comfort, and a restorative atmosphere. However, the hypothesized physiological changes in EEG-measured arousal and valence were not statistically significant with the current methodology. The strong preference for indirect, low-intensity lighting highlights its importance in designing home environments that support evening relaxation and positive effects. The study highlights the value of a mixed-methods approach and points to the need for continued research to bridge the gap between subjective experience and objective physiological measures in the field of environmental psychology and lighting design.

Disclaimer

The development of this master thesis involved the use of Artificial intelligence (AI) tools to assist in various aspects of the research and writing proses.

Tools utilised are:

- Claude Sonnet 4 in script development for data handling in Google Apps and Google Colab.
- Gemini 2.5 for initial result analysis and significant difference analysis from EEG Arousal and Valance calculations
- Chat GPT for grammar suggestions and spelling

It is crucial to emphasise that while AI tools have been used to assist this process, are all text critically reviewed and only used to enhance the process.

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