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A Matter of Position: How luminaire placement modulates the perceptual and neural impact of LED flicker

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Abstract

The general adoption of energy-efficient LEDs has introduced non-visual challenges such as flicker. Often, as a by-product of lower-quality drivers. While typically flicker is seen as a nuisance, this thesis aims to explore the impact of flicker through the lens of a lighting designer, asking the main research question: Does the negative impact of a flickering luminaire change depending on where you position it?

To see whether there is a correlation between position and frequency, a 2x2 experiment design was set out. It tested a low (60Hz) and a high (200Hz) frequency, with the luminaire being either positioned as general overhead lighting or as task lighting in the participant's peripheral visual field. Subjective data were gathered through questionnaires, as well as objective data were measured with an EEG. Fifteen participants performed a card-sorting task under the four lighting scenarios. The results show that, subjectively, 60 Hz lighting was most disturbing, especially in the task lighting position. However, these subjective measures were not reflected in the objective Gamma Bandpower. Indicating that the participants might have *felt* like it was disturbing, their physiology did not reflect that. This shows the disparity between perceived experience and our physiology. The research concludes that, as a lighting designer, when creating a human-centred design, we should look beyond our measures; in the end, the user's feeling of discomfort is the ultimate benchmark. It also strongly suggests that any luminaire with potentially noticeable flicker should be kept out of the peripheral visual field.

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List of Abbreviations

Abbreviation	**Full Term**
EEG	Electroencephalography
Hz	Hertz (frequency)
TLA	Temporal Light Artifact
M	Mean
SD	Standard Deviation
t	t-value (from t-test)
p	p-value (statistical significance)
HA	Alternative Hypothesis
H0	Null Hypothesis
γ (Gamma)	Gamma brainwave / EEG gamma bandpower
LED	Light Emitting Diode
CFF	Critical Flicker Fusion (threshold)
Likert	Likert scale (subjective rating scale)
TL	Task Lighting
GL	General Lighting
2×2	Two-by-Two Experimental Design

Introduction

From an energy efficiency drive are LED luminaires at a rapid speed implemented in building environments. It leaves us with the question: Is this a humanistic approach? In prioritizing efficiency, there is a risk that we neglect the potential health impacts, discomfort, and reduced performance that can arise from compromised lighting quality. (Rider et al., 2012)(Bullough, Hickcox, Kathryn S. W. E. A. T. E. R. et al., 2013)

Light goes beyond what we see, our visual perception; it is a fundamental physiological regulator. In a way, it orchestrates our circadian rhythm, circadian rhythm dictates the cycle of energy, rest, and focus. Inherently, our bodies are attuned to the dynamic qualities of natural daylight. But with the increase of indoor environments that are characterized by static, artificial lighting, we create a significant divergence from the natural conditions to which we are adapted.

The disparity in this leads to a primary concern: are the benefits of LED lighting being overlooked without a full consideration of their potential human-centric drawbacks? The non-visual effect of lighting is a key element in this discussion, particularly Temporal Light Artifacts (TLAs), flickering is part of TLA, and is most commonly known. Flicker occupies a 'grey area' of perception; at certain frequencies, it is noticeable to some individuals, and others it isn't.

Flicker is often associated with discomfort; however, the different characteristics are still being researched. It often occurs as a by-product of cost-effective LED drivers; these are often chosen in building projects to meet the sustainable targets. This creates a paradox where the pursuit of an environmentally conscious image may accidentally compromise the well-being of occupants.

As lighting designers, the goal is to optimize a space, not only for visual comfort but also for humanistic comfort. A primary tool to achieve this would be luminaire positioning. There has been separate research done in investigating the effects of flicker and luminaire placement on workspace optimization, but a significant research gap exists at the intersection of these two elements. There is evidence-based guidance missing on how the negative effects of flicker are modulated by the position of the light source. Furthermore, the subjective nature of comfort is often difficult to quantify, as individuals can lack the specific vocabulary to express their perceptions. This thesis aims to bridge that specific gap by implementing an objective physiological measurement (EEG) to validate subjective experiences.

The main aim of this thesis is to provide evidence-based recommendations for lighting designers on the placement of luminaires that show flicker. The research questions whether discarding a flickering luminaire is always the necessary solution, and it explores if the negative perception of flicker is context dependent.

The primary research question for this thesis follows:

How do flicker frequencies, 60 and 200 Hz, and luminaire position, general and task lighting, influence human comfort and cognitive performance, as measured by both subjective ratings, Likert scale, and objective EEG data?

The overarching goal of this study is to investigate the combined impact of LED flicker frequency and luminaire position on human perception and neurophysiological activity in a controlled lab environment.

To achieve this aim, the following objectives were established:

1. To quantify the perceived comfort, valence, and task difficulty under different lighting conditions.
2. To measure changes in EEG bandpower (alpha, Beta, and Gamma) as an objective correlation to cognitive load and stress.
3. Analyzing the correlations between these subjective and objective measurements.

For this study the following hypotheses will be tested:

Hypothesis 1: The Effect of Luminaire Position

- HA: Task lighting, positioned in the peripheral visual field, will cause a higher reported task difficulty and a greater change in neural activity associated with focus (Gamma power) than general lighting positioned centrally.
- H0: There is no significant difference in perception or neural activity between task lighting and general lighting positions.

Hypothesis 2: The effect of flicker frequency

- HA: Lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort than lighting at 200 Hz.
- H0: There will be no significant difference in task difficulty and neural activity (Gamma power) between 60 Hz and 200 Hz lighting.

Hypothesis 3: Correlation between subjective and objective

- HA: There will be a positive correlation between subjectively reported task difficulty or discomfort and objectively measured EEG bandpower indicative of cognitive load or stress.
- H0: There will be no significant correlation between self-reported scores and EEG measurements.

The significance of the study is especially found critical as modern life increasingly confines us to indoor spaces. It is important to understand the impact of artificial environments on our well-being. This thesis aims to evoke a discussion on the importance of a nuanced perspective in lighting design. And that there will be acknowledgment that the proclaimed benefits of technology like LED may have hidden costs, and that the phenomenon flicker may have context-dependent effects. The findings will support a more human-centered design ethos, with evidence that contributes to bridging the gap between design intuition and scientific research.

The thesis is structured by a literature review, giving the state-of-the-art knowledge, with the review, the research gap is highlighted. From an established research gap, the hypotheses will be defined. In the chapter methods, the strategy of the procedure is explained. In testing method and set up, the methodology for the hypothesis will be defined, as well as the set up of the experiment. In results, the findings of the experiment will be visualized to be further explain

Literature review

This literature review emphasizes the importance of light, including the dynamic properties of light and its influence on physiology and cognition. With flicker as the key focus, the purpose of this literature review is to examine the impact of key light parameters (spectrum, intensity, duration, and distribution). With every key parameter, there will be a focus on specifically how flicker interacts with these parameters.

The Literature review is structured by following the parameters of light. It will first explore the light spectrum, understanding how wavelength composition might influence the perception of flicker, and the sensitivity of the visual and non-visual reaction to flicker. Secondly, the relation between light intensity and flicker. Third, the duration of light exposure to flicker conditions, from acute periods to chronic effects. Finally, the spatial distribution of light includes the contrast between general and localized flickering. This will be explored for its role in visual comfort, distraction, and task performance.

By integrating these parameters, the aim is to provide a thorough understanding of the complexity and impact of flicker. This will provide a groundwork for further research on how we can optimize lighting environments and conditions.

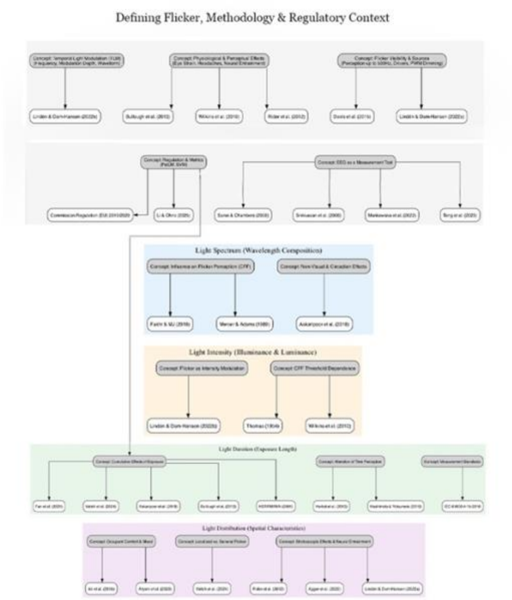

Figure 1- Literature Review Diagram

Defining flicker in the context of lighting

In lighting design and science, flicker is defined as the temporal light modulation (TLM) of a light source. Flicker is characterized by rapid and repetitive fluctuations in the luminous output. All electric light sources exhibit some degree of flicker, but it is particularly relevant for the modern Light Emitting Diode (LED). Thus, due to the nature of the systems, they are based on their power supply and control mechanisms.

These light modulations can be periodic, occurring at a consistent frequency, or non-periodic. The core variables that define flicker include:

- Frequency: measured in Hertz (Hz), this is the rate at which the light output fluctuates per second. Human sensitivity to flicker is frequency dependent.
- Modulation Depth: Typically expressed as a percentage, this represents the magnitude of the light variation relative to its average output. A higher modulation depth indicates a more pronounced fluctuation.
- Waveform: This describes the shape of the light output over time (e.g., square wave, sine wave).

Flicker can be categorized as perceptible, visible to the human eye, or imperceptible, occurring at frequencies above the Critical Flicker Fusion (CFF) threshold. Even when flicker is not perceived, it can induce physiological responses, which is why flicker can be a non-visual effect of lighting.
Physiological responses can be entrainment of neural oscillations in the visual cortex and may be linked to subjective reports of eye strain, headaches, and general malaise. Therefore, understanding flicker is a critical component of lighting design and research. (Wilkins et al., 2010)

The visibility of flicker depends on the interaction between frequency, modulation depth, and intensity levels. (Davis et al., 2015) found that flicker perception extends to much higher frequencies than previously recognized. Under appropriate conditions, humans were able to detect artifacts at 500Hz. This expands the understanding of perceptual sensitivity and the assessment of potential health effects.

In a thorough risk assessment of LED lighting, (Rider et al., 2012) examined the effects of both visible and imperceptible flicker. The analysis found that flicker occurring below the threshold of conscious perception can still produce measurable physiological responses. This challenges traditional assumptions about the safety of imperceptible temporal light modulation.

Furthermore, (Bullough, Hickcox, Kathryn S. W. E. A. T. E. R. et al., 2013) researched the connection between temporal light modulation, visual task performance, and the subjective perception of lighting quality. Their research demonstrated a direct correlation between flicker and reduced assessment of comfort. This confirmed that flicker can degrade the perceived quality of illumination even when observers do not visually detect its presence.

Flicker is not an inherent aspect of a light source, such as an LED chip, but rather a characteristic of the entire lighting system. The creation of flickering is mainly linked to the conversion of Alternating Current (AC) power into the Direct Current (DC) required by solid-state light sources; this process is managed by a driver.

Standard European AC power supply oscillates at 50 HZ, creating a fluctuation in the electricity power delivered to the luminaire. The quality of the LED driver determines how effectively the AC ripple can be smoothed into a stable DC output. As explained in guides for the lighting industry, such as that by (Lindén & Dam-Hansen, 2022a) from the Danish Technical University (DTU), lower-quality drivers may pass on inconsistent fluctuations, which cause the LED to rapidly dim and brighten and therefore produce flicker.

Moreover, dimming controls are a significant source of TLM; their most common method is the Pulse-Width Modulation (PWM), which operates by switching the LEDs on and off at a very high frequency to control the brightness. If the switching frequency is too low or the driver is not aligned to the dimmer, it can also produce a pronounced flicker.

Eco-design regulation (EU) 2019/2020 addresses these issues directly by setting mandatory limits on flicker (pstLM) and stroboscopic effects (SVM) for all lighting sources sold on the market. By introducing this regulation, they acknowledge that flicker is a systematic issue, managed by the interaction and quality of the electronic components, rather than the light source itself. (*Commission Regulation (EU) 2019/2020,* 2019)

Light is an essential component of the human experience, not only influencing our ability to perceive the world but also our physiology, cognition, and overall well-being.
Aside from its fundamental role in vision, light's dynamic characteristic, structured in the parameters of light, consists of light spectrum, intensity, duration, and distribution, which exert significant non-visual effects on biological processes like circadian rhythms and brain activity. While the static properties of light have been studied, they were earlier described as the key parameters of light: spectrum, intensity, duration, and distribution. The dynamic temporal light modulations, particularly the phenomenon of flicker, rapid fluctuations in light intensity, represent a critical, yet often overlooked, dimension of environmental lighting. Despite the modern LED lighting's energy efficiency, it often introduces flicker, raising concerns about its potential impact on human health and performance.

The European Union (EU) has established a framework to quantify and limit flicker in light sources. This is because the potential for health and performance issues has risen with the fast adaptation of LED lighting. It has brought significant progress in energy efficiency but also created potential in health issues, varying from eye strain to headaches and more.

The traditional metrics that are used are Flicker Index and Percent Flicker; however, it was found to be insufficient to fully characterize the complexity of the waveform produced by modern LED drivers. As a consequence, the industry has standardized on two metrics that form the foundation of current European regulations:

1. Short-term Light Modulation (P_{st}^{LM}): The 'st' stands for short-term, which indicates a brief interval. This metric quantifies the likelihood of a human observer directly perceiving flicker. The regulatory limit is set such a value of P_{st}^{LM}=1.0, which represents the average visibility threshold. For a light source to be compliant, it must therefore have a value less than or equal to 1.0.
2. Stroboscopic Visibility Measure (SVM): This metric quantifies the possibility of a TLM to create stroboscopic effects, where a moving object appears to be. Moving in discrete steps of even backward. The regulatory limit is set at SVM ≤ 0.4, although this has been subject to review for certain applications.

Since Denmark is a member of the EU, the main regulation regarding governing flicker is the Ecodesign Regulation (EU) 2019/2020. On September 1, 2021, this regulation came into full effect. It sets a mandatory performance requirement for light sources and separate control gears placed on the EU market. (*Commission Regulation (EU) 2019/2020,* 2019)

This law crucially commands that all LED and OLED (Organic Light-Emitting Diode; pixels that emit their own light, creating perfect high contrasts and blacks), must meet the performance standard for flicker defined by P_{st}^{LM} and SVM. The luminaire at full load must meet $P_{st}^{LM} \leq 1.0$, and the stroboscopic effect metric must be SVM ≤ 0.4. With this regulation, it is ensured that lighting products sold across the EU and specifically in Denmark are not only energy-efficient but also meet a minimum standard for safety and visual comfort.

Worth noting is also the IEEE std 1789-2015, while this is not a legally binding regulation in Europe, it does provide a risk-based assessment for recommending safe levels of flicker based on modulation depth and frequency.
Although the P_{st}^{LM} and SVM metrics are the ones that are required for legal compliance in Denmark, this document has had a big influence in raising awareness and guiding manufacturers. (*Commission Regulation (EU) 2019/2020,* 2019; Li & Ohno, 2025)

Light Spectrum (Wavelength Composition) & Flicker

Light spectrum

Light, as perceived by humans, is a narrow band of the electromagnetic spectrum, with its composition referring to the distribution of different wavelengths (colors) within that band. The complete visible spectrum consists of wavelengths from approximately 380 nanometers (violet) to 700 nanometers (red), with white light containing a mixture of these various wavelengths in different proportions.

The key metrics, like Correlated Color Temperature (CCT), provide a simplified representation of this spectral distribution. This can indicate the “warmth” or “coolness” of a light source. Where lower CCT values (typically 2700K-3000K) indicate warmer, more yellow-red light similar to incandescent sources. While higher CCT values *5000K-6500K) represent cooler, more blue-white light characteristics of daylight conditions. (Fakhr & MJ, 2018)

Flicker, on the other hand, describes the rapid temporal modulation of light output. Occurring at frequencies that may range from a few hertz to several kilohertz. Often imperceptible to the conscious eye but able to elicit a range of physiological and perceptual responses. (Lindén & Dam-Hansen, 2022b)

The threshold of flicker perception varies among individuals and depends on factors such as modulation frequency, modulation depth, and ambient lighting conditions.

The interplay between the light spectrum and flicker extends beyond conscious perception, which influences various physiological and non-visual responses. This includes the intricacies of the circadian rhythm. While their work addresses a wide range of light parameters, it does provide a suitable framework for understanding how flicker, especially when considered in conjunction with specific spectral compositions, might contribute to non-visual forming effects, such as the disruption of circadian rhythms, alterations in autonomic nervous activity, and subjective experiences of fatigue. A primary driver of our circadian rhythm is the spectral composition of light, and therefore, the presence of flicker within different spectral ranges could potentially amplify the impact on our circadian clock.

Light Intensity (Illuminance/Luminance) & Flicker

Light intensity can be characterized through two photometric quantities: illuminance and luminance. Illuminance is measured in lux and can be calculated by quantifying the luminous flux incident on a surface per unit area. Illuminance represents the amount of light falling on a given surface.

Luminance, measured in candelas per square meter (cd/m2), describes the luminous intensity per unit projected area of a light source or illuminated surfaces as perceived by an observer.

These photometric quantities form an important foundation for understanding how light interacts with human visual and physiological systems.

Typical intensity levels can vary considerably across different environments and applications. Indoor office environments typically maintain illuminance levels between 300-500 lux, while outdoor daylight can reach 10.000-100.000 lux depending on weather conditions and time of the day. For residential lighting, the intensity is generally at lower levels, ranging from 50-200 lux for ambient lighting to 500-1000 lux for task-specific use. The understanding of these intensity levels is crucial since they form an important parameter for evaluating lighting.

Flicker as intensity modulation

Flicker represents the rapid temporal modulation of light intensity; it creates a periodic variation. This phenomenon is characterized by its modulation depth, also referred to as flicker percentage or flicker index, which quantifies the relative magnitude of intensity variation during each flicker cycle. Described by (Lindén & Dam-Hansen, 2022b) in their guide to flicker for the lighting industry, modulation depth serves as a critical parameter that determines both the perception and potential impact of a flickering light. Higher depths in modulation indicate a bigger change in intensity during the flicker cycle. This makes the temporal variations more noticeable and potentially more physiologically significant.

The mathematical relationship between average, maximum, and minimum intensity values define the depth of the modulation. With a deeper modulation, more pronounced temporal intensity variations are created. (Lindén & Dam-Hansen, 2022b)

The threshold at which flicker becomes imperceptible, known as the critical flicker fusion (CFF) frequency, is directly influenced by retinal illuminance. With a higher light intensity, the CFF threshold generally increases, meaning that flicker is detectable at higher frequencies under brighter conditions. According to the paper of (Thomas, 1954), it is implied that the potential for flicker to cause distraction or discomfort is not static but changes with the ambient light level.

In the paper by (Wilkins et al., 2010), the importance of understanding this relationship when evaluating LED lighting flicker and connected health concerns is emphasized.

Noting that modulation characteristics significantly influence the biological effects of temporal light variations.

The perception of the spectrum of a light source can be altered dynamically with the presence of flicker, specifically considering the temporal limitations of the visual system. The Research done by (Mercer & Adams, 1989) illustrates that the ability to perceive flicker, quantified as Critical Flicker Frequency (CFF), is influenced by the stimulating wavelength. This suggests that the stability of a light source perceived and thus its perceived spectral quality is linked to its temporal characteristics. While

Light Duration (Timing and Exposure Length) & Flicker

The duration of flickering light is an indispensable variable. Prolonged exposure can lead to visual fatigue and a cumulative negative impact on comfort and performance, even when the flicker is above the CFF and not consciously perceived. (HERRMANN, 2001a)

The temporal dynamics of light can entrain neural oscillations in the visual cortex, a phenomenon where brainwave patterns synchronize with the frequency of the flicker. This neural entrainment can influence cognitive processes with ramifications. While some frequencies potentially enhance certain tasks, others may be disruptive. (Fan et al., 2021)

The exposure duration determines the extent of its subsequent behavioral consequences and the neural entrainment. Prolonged exposure to TLM can lead to adaptation and fatigue. Research done by (Veitch et al., 2024) indicates that flicker impacts eye movement and brain functions. The study suggests that even when the effects are initially subtle, they can lead to greater visual fatigue over time compared to shorter exposures. In line with this, the work of (Askaripoor et al., 2018) on non-image forming effects demonstrates that temporal modulation can affect autonomic nervous activity and induce fatigue, subsequently impairing performance.

Beyond the physiological fatigue, it has been shown that flicker can alter the subjective perception of duration itself. Studies by (Herbst et al., 2013) demonstrate that perceived flicker can dilate subjective time. The mechanism for this may be linked to neural entrainment; (Hashimoto & Yotsumoto, 2018) found that the amount of time dilation experienced corresponds to the amount of neural entrainment measured by EEG. This suggests that flicker does not only occur within time but can actively change our experience of time.

Sustained exposure to flicker may negatively impact tasks requiring sustained attention or vigilance, from a cognitive and perceptual standpoint, as investigated by (Veitch et al., 2024). Furthermore, perceived discomfort tends to be cumulative. Even when the temporal variations are not consciously identified by the observer, Bullough et al. (2013) confirmed that subjective reports of discomfort and degraded lighting increase with the duration of flicker exposure in visual task performance.

Light Duration in Flicker

There are two relevant international organizations that focus on standardization. Applicable for this project are the IEC (International Electrotechnical Commission) and the CIE (International Commission on Illumination). The IEC develops standards for electrical, electronic, and other related technologies. While CIE focuses on the science and art of light and lighting.

The official papers of these organizations are hidden behind a paywall, making it difficult to access and refer to in the literature study. Therefore, detailed technical documents and other content of IEC and CIE cannot be directly reviewed here. However, publicly available summaries and secondary resources indicate that both organizations provide frameworks for flicker metrics, such as the PstLM and SVM. In the IEC's technical Report 61547-1:2020 (*IEC-61000-4-15-2010*), it is specified that the recommendation for measuring PstLM is 180 seconds, while CIE Technical Note 012:2021 suggests that 60 seconds or more is already sufficient. For the SVM metric, there is less prescriptive guidance. There is a suggestion that, commonly, 1-second or longer measurement durations are used to measure SVM. Longer durations are generally associated with a potential enhancement of accuracy, though the impact on SVM variability remains under discussion.(Li & Ohno, 2025; Lindén & Dam-Hansen, 2022a)

Light Distribution (Spatial Characteristics) & Flicker

The spatial arrangement of lighting, or so-called light distribution, within an environment influences the occupant comfort and performance. Parameters for light distribution consist of uniformity, directionality, and the presence of glare; these parameters define the visual conditions of a space. (Ali et al., 2015)

As stated in the literature review by (Aryani et al., 2020), the characteristics of the visual environment directly affect the mood and well-being of occupants.

Interplay between flicker and light distribution

The perceived impact of flicker is essentially linked to its spatial distribution. A key distinction, and a main aspect of this study's design, is whether the flicker is localized or disturbed across the entire visual field. For example, a flickering LED that is located as general lighting may be perceived as more pervasive, as it affects the entire visual field. Instead of a flickering LED located as task lighting, mainly lighting the peripheral vision field, this might lead to a higher contrast and more temporal dynamics, which could be more intrusive for tasks performed directly under it.

(Pikovit44 et al.)

Figure 2 - Peripheral vision field of vision. Adapted by L. Steenblik Hwang from (Pikovit44 et al.)*, iStock, & Getty Images Plus (n.d.). SN Explores. https://www.snexplores.org*

Temporal light modulations can also produce stroboscopic effects, a disruptive illusion of motion created by light modulations. As explained in the industry guides by (Lindén & Dam-Hansen, 2022a) and in a risk assessment by (Rider et al., 2012), any effect of disruptive illusions is a significant source of visual distraction. Eye movements can also be affected by the spatial pattern of flicker, which can lead to a greater neurological strain and visual fatigue, an area investigated by (Veitch et al., 2024). The way in which flicker is distributed throughout the space, whether it mainly affects the central or peripheral visual field, may therefore have a direct relevance to cognitive performance.

Another pertinent factor is the spatial distribution of neural entrainment itself. (Agger et al., 2022) found that flicker induces neural entrainment with a specific spatial pattern in the brain. This suggests that a disturbed flicker source could entrain a wider cortical area, which potentially can lead to a more significant physiological and cognitive impact.

In the research by (Tong et al., 2023), evaluating lighting conditions by using neurophysiological data is supported. In the paper, they successfully used EEG to identify preferred illuminance levels in office environments.

Electroencephalography (EEG) and perception of flicker

To objectively quantify the neural responses to different lighting scenarios, this study utilizes electroencephalography (EEG). This methodology offers a direct measurement of the electrical activity in the brain. This will provide a physiological basis for understanding the impact of environmental stimuli like flicker on cognitive states.

EEG signals are typically analyzed across established frequency bands that correspond to various cognitive and behavioral states. Defined by (Sanei & Chambers, 2008), these fundamental rhythms include delta (δ), theta (θ), alpha (α), and beta (β). Every band offers specific information regarding a participant's neural processing, making EEG a suitable method to use for the assessment of temporal light modulation effects.

Since the brain's neural oscillations can synchronize with the frequency of a flickering light source, the application of EEG is particularly relevant for flicker research. Research by (Srinivasan et al., 2006) shows that steady-state visual evoked potentials (SSVEPs), a type of EEG response, are very sensitive to flicker frequencies. This study supports the use of EEG to examine frequency-specific neural responses during cognitive tasks.

Other theoretical support is given by (Mankowska et al., 2022), who explored the neuropsychological mechanisms behind flickering light stimulus processing. The research provides a foundation for understanding the complex interactions between temporal visual processing and cognitive function. The executable of neurophysiological data in applied settings is supported by the work of (Tong et al., 2023). They successfully utilized EEG to identify preferred illuminance levels in office environments.

By integrating EEG as a methodology, a common challenge in environmental research is addressed: the difficulty for participants to articulate complex sensory experiences. Non-specialists may lack the specific vocabulary to express and describe their perceptions of lighting, which can limit the depth of purely subjective data. Moreover, an individual's perceived experience may not always align with their underlying physiological responses.

By measuring objective, real-time data on the neural activity, the EEG will provide a valuable counterpart to the subjective data collected through questionnaires. This dual approach allows for a more holistic analysis, validating self-reported feelings against the physiological notes, and removing the pressure on the participants to verbalize and describe their experience.

Conclusion and Identification of the Research Gap

This literature review confirms that even when imperceptible, flicker, defined by its frequency, waveform, and modulation, can have a significant physiological and perceptual effect. These effects are further impacted by the intensity, duration, and spectral properties of the light. While regulatory frameworks exist to limit flicker, and separate research has investigated the impacts of flicker and luminaire position, a clear research gap remains.
The specific research gap is the lack of research that systematically investigates the interaction between flicker frequency and luminaire position. It is unknown how the negative perceptual and physiological effects of a known flicker frequency are modulated when the position is changed. For this study, the focus is on the general (central) visual field and the task (peripheral) visual field.

In this study, the aim is to address this gap by selecting two frequencies, a low and a high frequency, for comparison and contrast. For a low, potentially visible frequency, 60Hz was chosen; it lies in a critical range where flicker is not always consciously perceived by everyone, but it is known to be physiologically active. For a high frequency, 200Hz was chosen, as it is a high-frequency control condition that is well above the established visual fusion threshold; therefore, it should be imperceptible to all participants. By utilizing these two frequencies in two distinct positions, this study will provide direct evidence-based insights on how the spatial context of a flickering light source impacts human comfort and cognitive load.

Theoretical Grounding for Hypotheses

Grounded in the findings and gaps identified within the existing literature, three hypotheses were formed. This section elaborates on the connection of the hypothesis to the theoretical framework.

Hypothesis 1: The Effect of Luminaire Position

- **HA**: Task lighting, positioned in the peripheral visual field, will cause a higher reported task difficulty and a greater change in neural activity associated with focus (Gamma power) than general lighting positioned centrally.
- **H0**: There is no significant difference in perception or neural activity between task lighting and general lighting positions.

The effect of the luminaire position is based on the spatial distribution of the light. In the work of (Veitch et al., 2024) it is suggested that the spatial pattern of flicker can affect eye movement, which can lead to a greater neurological strain. This aligns with the prediction that a luminaire located in the peripheral visual field (task lighting) may be more intrusive and would require greater cognitive resources to ignore, compared to a general luminaire located centrally. Research by (Agger et al., 2022) found that neural entrainment is induced by flicker, with a specific spatial pattern in the brain. This provides a physiological basis for hypothesis 1. It suggests that cortical areas could be entrained differently when a flicker source is located peripherally. That could potentially lead to a more notable cognitive impact, which is one of this study's objectives; to measure that through both subjective difficulty ratings and objective EEG data.

Hypothesis 2: The Effect of Flicker Frequency

- **HA**: Lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort than lighting at 200 Hz.
- **H0**: There will be no significant difference in task difficulty and neural activity (Gamma power) between 60 Hz and 200 Hz lighting.

The effect of flicker frequency is built upon the fundamental principles of flicker perception, and with that, the physiological effects. The specific frequencies are both carefully chosen. The choice of 60Hz is based on its imperceptible yet physiologically relevant range. In contrast, 200Hz serves as a high-frequency control condition; this frequency is well above the typical Critical Flicker Fusion (CFF) threshold, and therefore not noticeable by the eye. In the research done by (Wilkins et al., 2010) as well as (Rider et al., 2012) it is established that flicker that occurs below the threshold of conscious perception can still produce measurable physiological responses and demean comfort. This paper directly supports that the 60Hz scenario will cause more disruption. Additionally, the findings of (Bullough, Hickcox, Kathryn S. W. E. A. T. E. R. et al., 2013) provide a strong basis for expecting a high report of discomfort and task difficulty in the 60Hz scenario compared to the 200Hz scenario. The research demonstrates a direct correlation between temporal light modulation and reduced subjective assessments of comfort.

Hypothesis 3: Correlation Between Subjective and Objective Measures

- **HA**: There will be a positive correlation between subjectively reported task difficulty or discomfort and objectively measured EEG bandpower indicative of cognitive load or stress.
- **H0**: There will be no significant correlation between self-reported scores and EEG measurements.

A challenge that has been found is the validation of subjective experiences; this is addressed in the third hypothesis, which has been a key theme in the literature review. Since participants can have trouble articulating complex sensory experiences, due to limitations in vocabulary or not knowing how to express themselves can cause a limitation to the depth of solely subjective data. To use EEG as a tool to bridge this gap is supported by the literature. The work of (Tong et al., 2023) uses EEG to identify preferred illuminance levels in office environments and utilizes the tool to validate subjective preferences. One of this study's goals is to apply a similar principle in the context of flicker. Research on steady-state visual evoked potentials (SSVEPs) done by (Srinivasan et al., 2006) established the sensitivity of EEG to flicker frequencies, which provides a theoretical basis for the expectation of a measurable neural response. The prediction of this hypothesis is therefore that the subjective reports of increased cognitive load under 60Hz lighting will be reflected by a measurable, corresponding change in EEG bandpower, which will therefore provide an objective validation of the perceived experience.

Testing Method and Set Up

This chapter goes into detail on the methodological approach that is used to investigate the impact of luminance flicker frequency and luminaire position on human perception, comfort, and neural activity. It covers the participants' sample, the study apparatus, the study's design, the step-by-step procedure, and the methods for data collection and presentation.

The study focuses on two specific flicker frequencies, 200Hz and 60Hz, selected based on their relevance to LED lighting systems and their potential to have physiologically significant effects. These two frequencies span between the imperceptible and the perceptible range of flicker, allowing for an assessment of temporal light modulation across different perceptual thresholds.

Theoretical framework

The study is based on previous research that has demonstrated that indoor environmental quality has a significant impact on physical and mental well-being, as well as work efficiency. Within lighting design, energy efficiency is broadly present, but this research prioritizes human-centered consideration. It recognizes that, within rapid technological development, sometimes compromised quality can lead to unintended side effects such as flickering.

There are varying effects on individuals caused by flickering, due to differences in sensitivity. Often, flickering is associated with negative connotations; however, as highlighted in the literature review, research has demonstrated potential benefits for focus, comfort, and even productivity if properly implemented. This study aims to bridge the gap between electrical engineering approaches to flicker analysis and human-centered lighting design.

The participants.

The participants were recruited through the personal network of the assessor. This varied from personal contacts to former classmates and other acquaintances. The requirements were the age and mental health. The targeted age group is between 18-40; other specifications were that they weren't allowed to be prone to getting headaches, have epilepsy, or be in an unstable mental state.
In total, 16 individuals participated in this study. The data from (p02) has been excluded from the final analysis due to unusable EEG recordings. This results in a final sample of n=15.
All participants are aged between 22 and 30 years old.

Via a pre-experiment questionnaire, the demographic data were collected. This captured information on age, gender, handedness, and visual impairments, as well as consent for data gathering and procedure.

Apparatus and Materials

Development of custom flickering luminaires
For the experimental design of this thesis, it is an absolute necessity to have precise control over both the flicker frequency and the luminaire position. This combination

could not be achieved with commercially available luminaires without complex and often expensive modifications. Because of that, a custom flickering luminaire was designed and created from scratch. The process of this development consists of technical challenges, iterative testing, and a lot of fine-tuning to achieve the required flicker, light stability, and performance.

Initial prototyping
As a start, various lighting technologies and control mechanisms were explored. Attempts were made to adapt more advanced lighting systems, such as DMX-controlled luminaires, to produce the 60Hz and 200Hz required flicker frequencies. However, during the prototyping stage, it became clear that high-quality LED lights often have an incorporated internal circuit that is designed to suppress flicker, making them inherently resistant to controlled manipulation of temporal light modulation. Conversely, lower-cost and simpler LED luminaires, often characterized by less advanced internal drivers, proved to be far more controllable to external control. This led to the strategic decision to utilize battery-powered LED lamps that were readily available; with their ease of manipulation, these battery lamps are the foundation for the custom luminaires.

Electronic Circuit design and control
The experiment revolves around two positions; for the ease of the experimental design, two identical lamps were created. To achieve the precise flicker control, each luminaire was equipped with an ESP32 microcontroller board, which allowed us to control it with Wi-Fi. By using a Pulse Width Modulation (PWM) signal, it was possible to manipulate the power supply to the LEDs, causing the flicker to be generated.

For each luminaire, a circuit was made on a breadboard, and consisted of the following key components, see Figure 3 the for circuit diagram:

- ESP32 Microcontroller: With the usage of Arduino IDE to program it, the ESP32 served as the brain of the system. The microcontroller generated an interval that created a precise PWM signal. The integrated Wi-Fi control allowed for a remote control, and the luminaires to be turned on and off from a distance. Minimizing disturbance during the experiment.
- MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor): The electronic switch of this system is the MOSFET. The MOSFET allows the LED can rapidly turn ON and OFF, it drives the PWM signal from the ESP32 to the MOSFET. The rapid change allows for a high-speed switching of the current to the LEDs, which is directly translated into the desired flicker frequencies. To achieve the high-frequency flicker, it is crucial that the semiconductor can handle the fast-switching speeds; the MOSFET was chosen for this ability.
- Resistors: into the circuit, multiple resistors were integrated for several functions:
    - Current limiting resistor: To limit the current flowing through the LED, a resistor was placed to prevent it from drawing excessive current. That could lead to overheating and damage, creating an unsafe scenario. This resistor was particularly important since the luminaires required the rapid switching at high frequencies.

- Gate resistor: To help with the control of the switching speed and to prevent oscillations, a resistor was connected to the gate of the MOSFET. This helped ensure a clean and stable PWM signal.

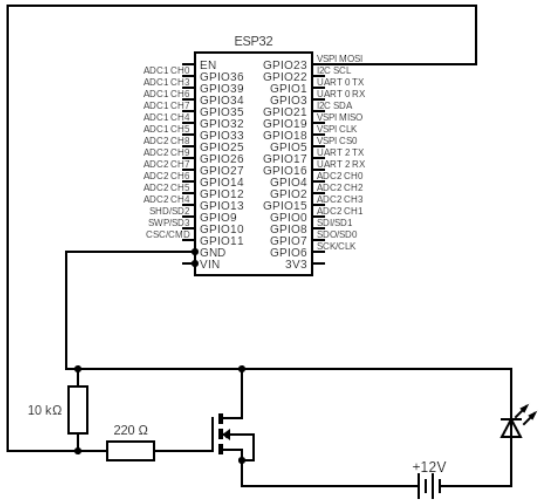

Figure 3 - Circuit diagram, showing the ESP32, MOSFET, LED, and resistors

Firmware Development and Flicker Waveform

The goal was to create a stable square wave PWM signal at exactly 60Hz and 200Hz. The firmware for the ESP32 was therefore developed in the Arduino environment. While the goal was to create a perfect ON/OFF signal, the basic internal electronics of the chosen battery-powered lamps introduced some complexities, which resulted in a less-than-ideal waveform. The primary focus was therefore not to achieve a theoretically perfect wave but rather to create a dominant and consistent fluctuation in the light output at the exact frequencies of 60Hz and 200Hz.
Through an iterative process of fine-tuning the interval and the pulse duration in the code, this was accomplished. Despite the hardware's limitations, this ensured that the luminaires produced a distinct and controllable temporal modulation that could be used for the experiment.

The firmware for the ESP32 microcontroller was developed in the Arduino Integrated Development Environment (IDE) to provide two primary functions: wireless remote control and precise flicker.

The ESP32 was programmed to act as a web server, which allowed for remote operation without having to disturb the participant during the experiment.

1. **Wi-Fi Connection:** At the start of the code, the ESP32 is connected to a local Wi-Fi network (`linksys`).
2. **Web Interface:** The HTML webpage is stored directly in the code; this is made for the ease of the experiment. When a user navigates to the ESP32's IP address in a web browser, it will be presented with a page that displays three buttons: "Flicker 1 (200Hz)," "Flicker 2 (60Hz)," and "Turn Off."
3. **State Management:** To manage the luminaire's current status (`OFF`, `FLICKER_FAST`, or `FLICKER_SLOW`), a state machine was implemented by using

an enum (LedState. When clicking on a button on the webpage, the interface updates the state variable, which immediately changes the luminaire's behavior. This approach ensured that there was a smooth and instantaneous transition between the remote laptop and the luminaires set up for the experiment.

Flicker Generation Logic

The flicker effect is managed within the main `loop ( ) function`. With this function, there is a continuous check of the `currentState`, and it knows how to execute with the corresponding flicker.

The flicker itself I created by using a simple yet effective technique:

1. `digitalWrite(ledPin, HIGH)`: This command sends a signal to turn the LED fully ON.
2. `delay()`: for a specific duration in milliseconds the program then pauses.
3. `digitalWrite(ledPin, LOW)`: This command turns the LED fully OFF.
4. `delay()`: The program pauses again for the same duration.

The square wave flicker is created by a cycle that repeats indefinitely, an ON-delay-OFF-delay. The frequency of this flicker is determined by the duration of the delays. For example, in the FLICKER_SLOW case, the code is:

```
delay(1000 / 120); // ON duration
delay(1000 / 120); // OFF duration
```

Each ON/OFF cycle takes `(1000 / 120) + (1000 / 120)` milliseconds. The total number of cycles per second (the frequency) is therefore `1000 / ((1000/120) + (1000/120))`, which equals **60 Hz**. See figure 4 for a snippet of the code.

A similar calculation for the 200Hz was done in the FLICKER_FAST case, `delay(1000 / 350`, with the final precise frequency was calibrated and validated using the Viso Systems flicker measurement tool, see figure 5 for measurement tool. This method, while simple, provided the stable and distinct temporal modulation required for the experiment. Figure 6, 7, 8 and 9 show the measurement results per flicker ratio per luminaire measured in position with see appendix 10 for the full Arduino Code.

Figure 4 - Snippet Arduino IDE code

Validation and Calibration

To create a valid experiment, it was a crucial step in the development to validate the generated flicker frequencies. The validation was performed by the usage of a professional flicker measurement tool, the Viso Systems Lab Flicker Measuring Tool. This tool allowed for precise measurements of the flicker and verifications of the dominant frequencies. Initial measurements showed variations and inconsistency; as a result, necessary adjustments and simplifications were made to the ESP32 code. With repeated testing and thorough modifications to the PWM parameters, eventually a stable, accurate frequency was achieved for both the 60Hz and the 200Hz. With this validation, it was ensured that the luminaires produced the intended experimental conditions for the study.

Figure 5 - LabFlicker flicker tester. Image courtesy of Viso Systems (n.d). https://www.visosystems.com/products/labflicker/ (Viso Systems - LabFlicker)

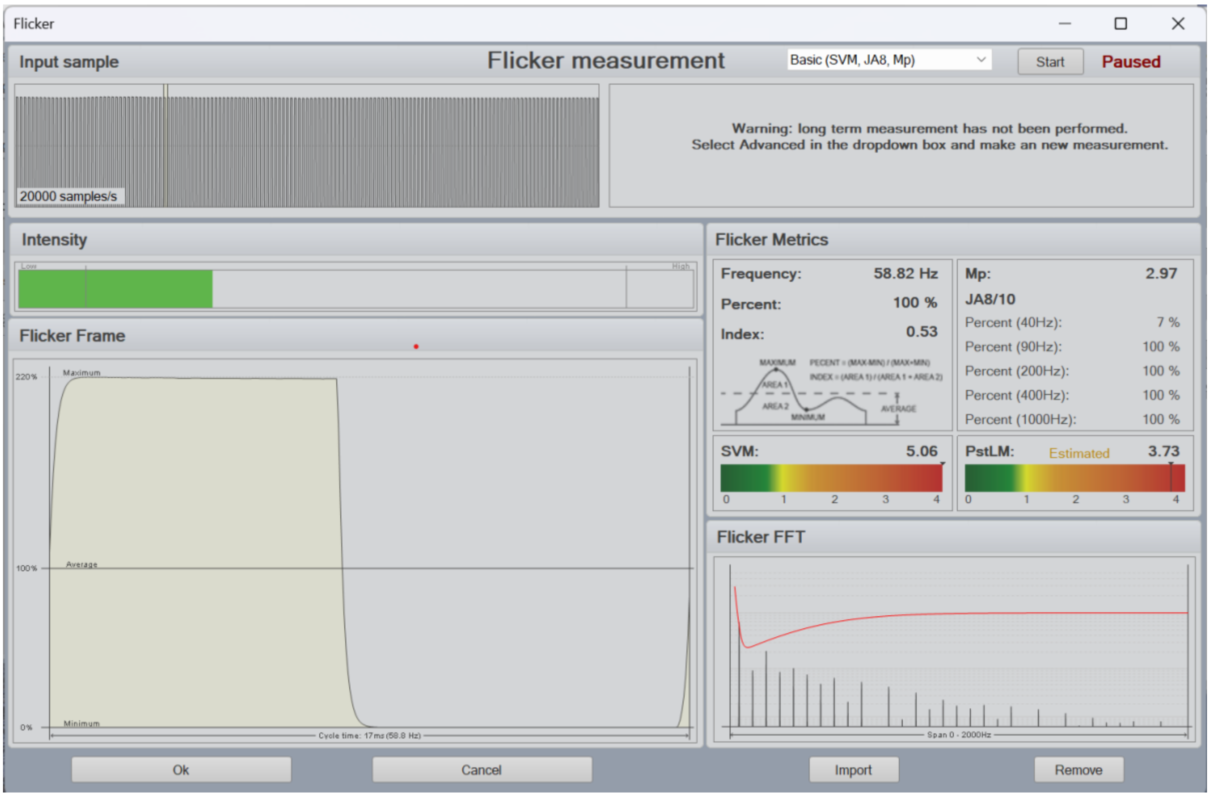

Figure 6 - Lab Flicker measurement - 60 Hz Task Lighting

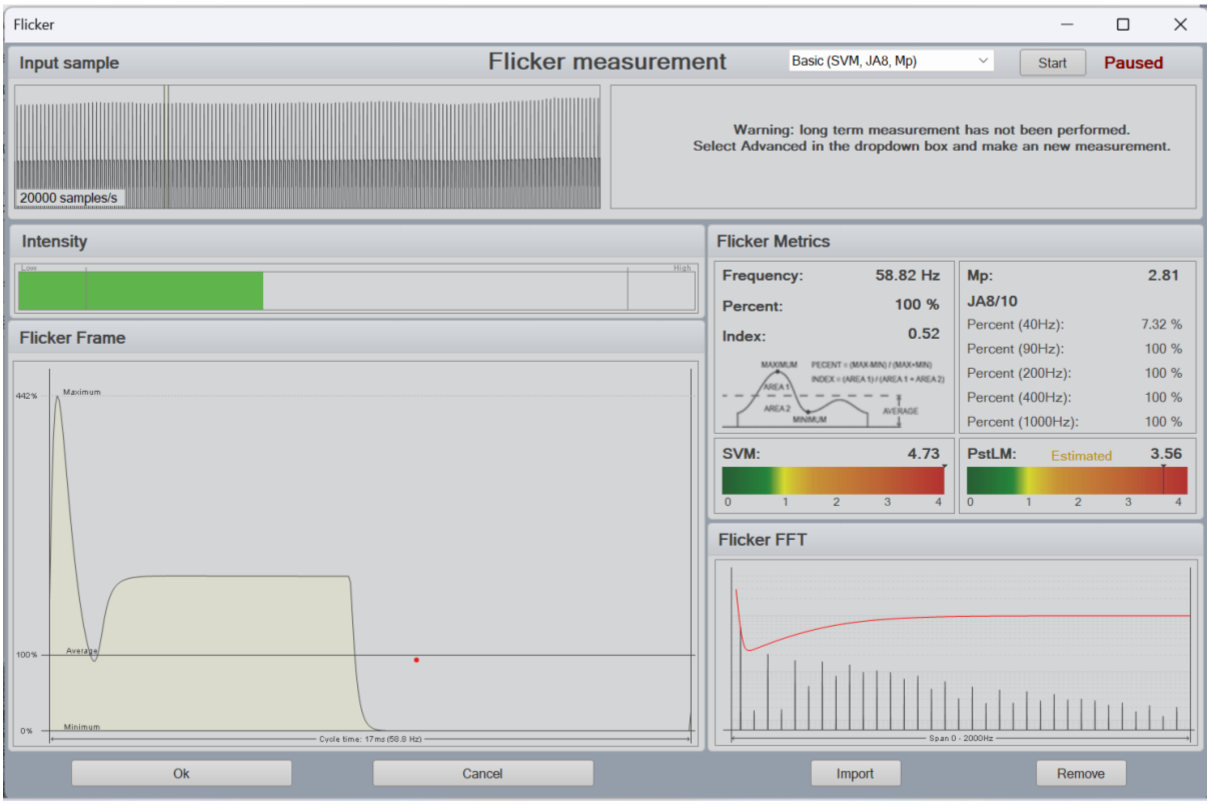

Figure 7 - Lab Flicker measurement - 60 Hz General Lighting

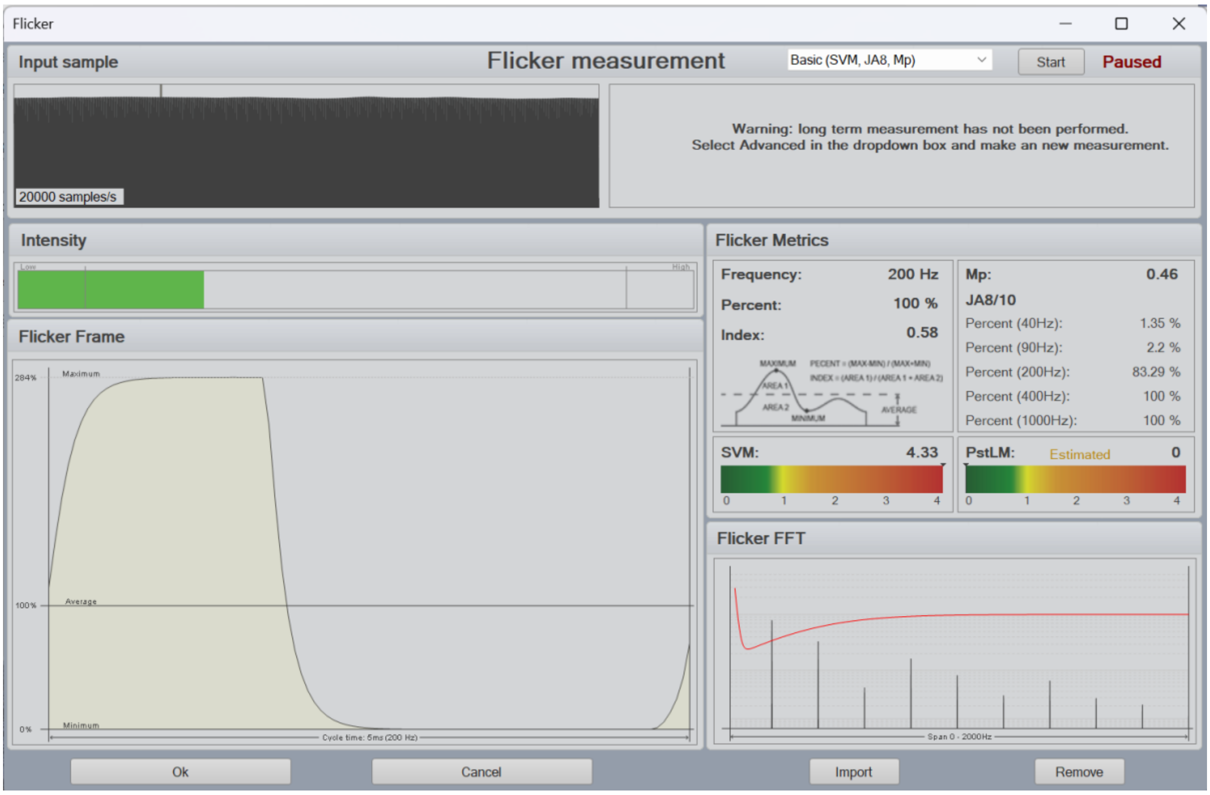

Figure 8 - Lab Flicker measurement - 200 Hz Task Lighting

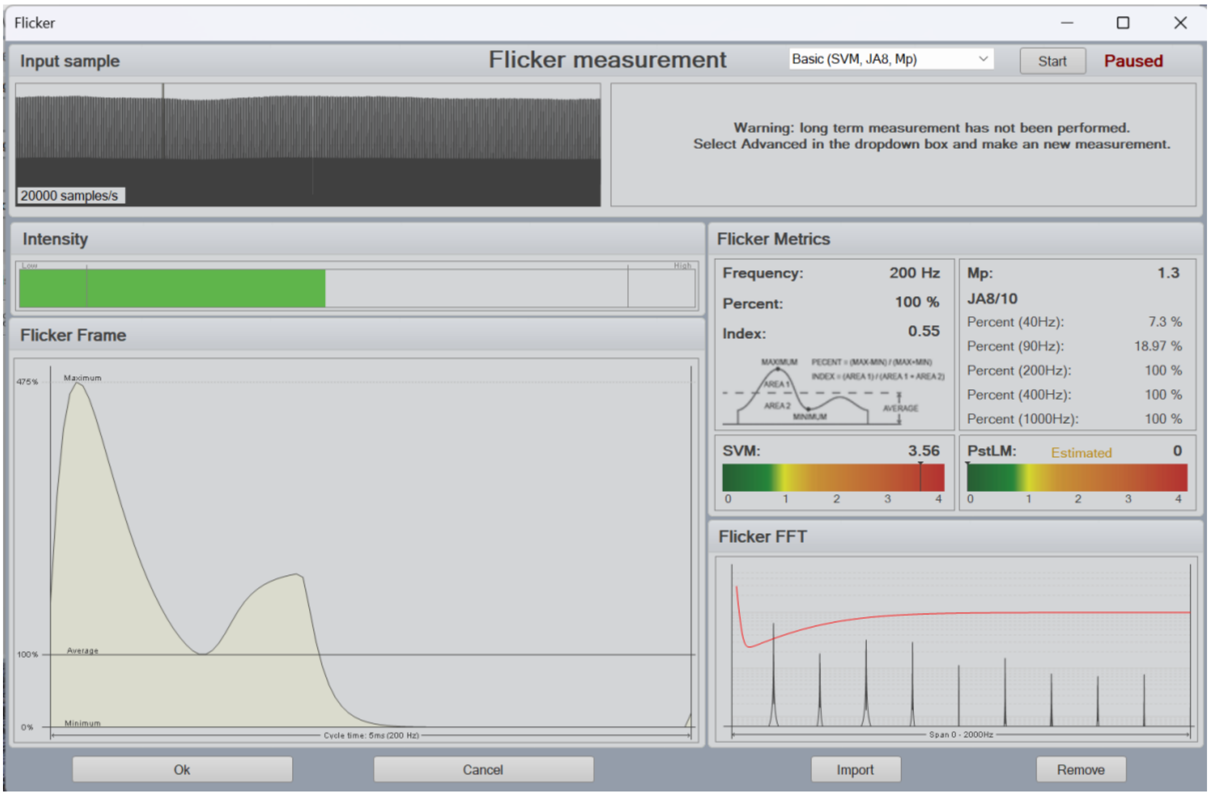

Figure 9 - Lab Flicker measurement - 200 Hz General Lighting

Final Luminaire Assembly
The final setup that allowed for the remote, wireless control of each lamp's frequency, enabling smooth transitions between experimental conditions without interacting with the luminaires during the sessions, is the two experimental luminaires, which consist of the chosen battery-powered LED. Each lamp is internally modified with an ESP32 board and a custom-built control circuit, see appendix 2-4. The measured CCT for the luminaire is 4112K with a lumen output of approx. 490lx., both measured with a handheld GL SPECTIS 1.0 Touch + Flicker spectrometer.

The Lighting Setup

The experiment was conducted in a controlled lighting laboratory at Aalborg University in Copenhagen. The setup consisted of two luminaire types to create four experimental conditions:
General Lighting: A ceiling-mounted luminaire, positioned above the participant. The general lighting luminaire is mounted 313 cm from the ground. Based on the already existing track mounted on the location side.
Task Lighting: A desk-mounted luminaire positioned in the participant's peripheral visual field. This luminaire is mounted 118 cm from the ground, angled in approximately 30-35 degrees.

Table 1 - Lux measurements of Luminaire, Materials and Reflection

Scenario	A General 200Hz	B Task 60Hz	C Task 200Hz	D General 60Hz
Lux measured centre of the table to light source	17lx	92lx	91	19 lx
Lux Measured 20 cm above Cards	3lx	25lx	25lx	3lx
Lux Measured 20 cm above the table	3lx	27lx	27lx	3lx

Both luminaires were programmed to operate at two frequencies: 200Hz, a high frequency generally perceived as stable and flicker-free, and 60Hz, a low frequency known to be perceptible and potentially disruptive.

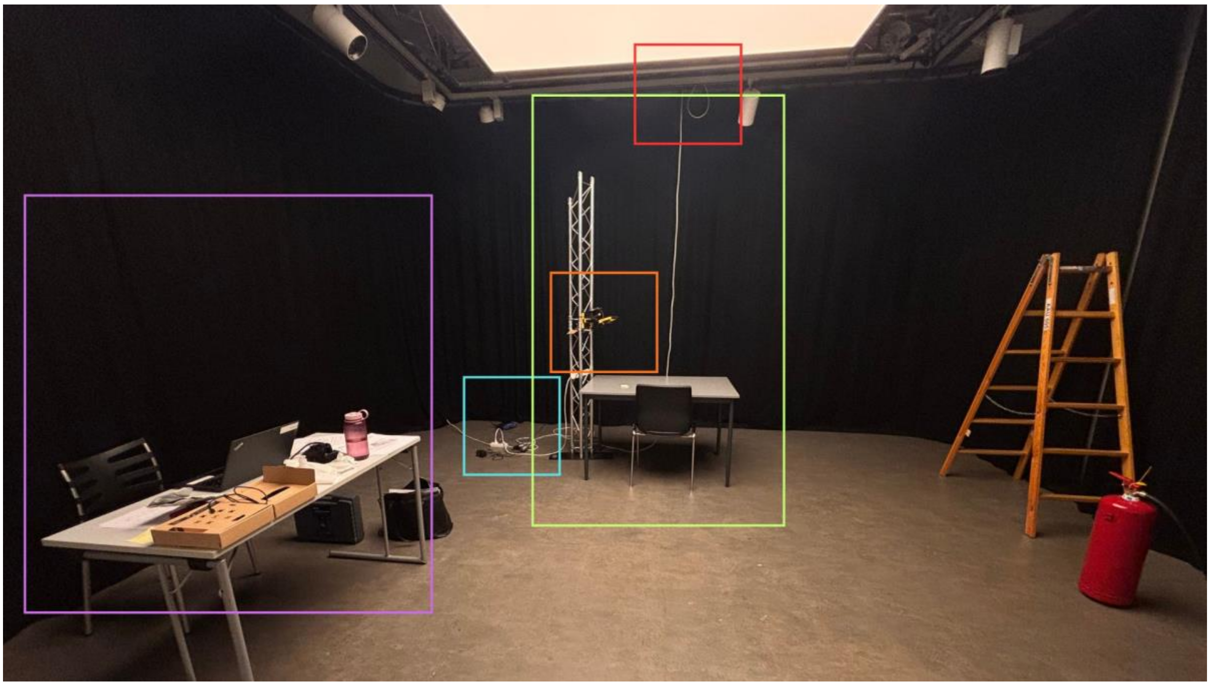

Figure 10 - Overview of the light lab and experimental test setup

In Figure 10, there is a visual overview of the experimental setup within the controlled laboratory environment. The setup of the experiment was designed to isolate the environment and minimize little interference from external light during the cognitive task test. The main components, as highlighted by the coloured boxes, are detailed below:

Purple: This is the station of the experimenter; the researcher is positioned at this control station, out of the direct line of sight from the participant. From here, the researcher can start the lighting scenarios via the wireless network, and the real-time EEG data is monitored, as well as the participant observation, to ensure the protocol is followed correctly.

Blue: The Wi-Fi router provides a wireless control network. This network is essential for the remote operation of the luminaires. It allows for instantaneously and wirelessly switching between the pre-programmed flicker frequencies 60Hz and 200Hz using a laptop. It ensured seamless transitions between the different scenarios.

Green: This is the participant station, where the participant is seated to perform the card-sorting task. In this setup, the general lighting luminaire is directly located overhead, and the task lighting luminaire is in the periphery. Making sure that the light setup was standardized, and all viewing conditions were the same for the participants.

Orange: The task lighting luminaire is positioned in the peripheral visual field of the participant. This setup represents the “task” lighting scenario, which is designed to test the impact of a localized non-central luminaire.
Red: This is the position of the general luminaire. Ceiling-mounted and positioned to provide illumination from directly above the participant. This scenario represents the “general” lighting scenario, affecting the entire visual field.

EEG System

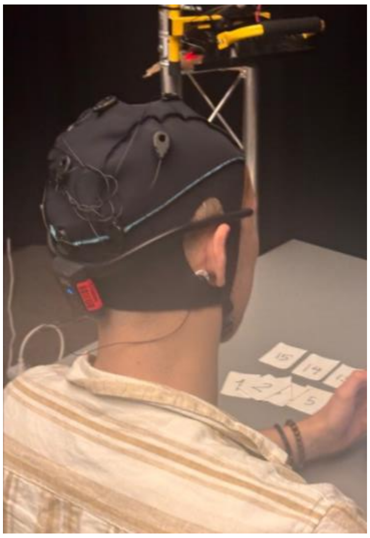

Figure 11 - EEG Headset installed on Participant

Neural activity was recorded using a g.tec Unicorn Hybrid EEG system see Figure 11 ofr installation on participant and Figure 12 for the layout of the software. This is a non-invasive headset capturing data from eight scalp electrodes according to the international 10-20 system, allowing for the measurement of electrical brain activity in real-time. This hybrid setup is connected to the computer through Bluetooth, making this headset easy to use for measuring while there is movement connected to the task.

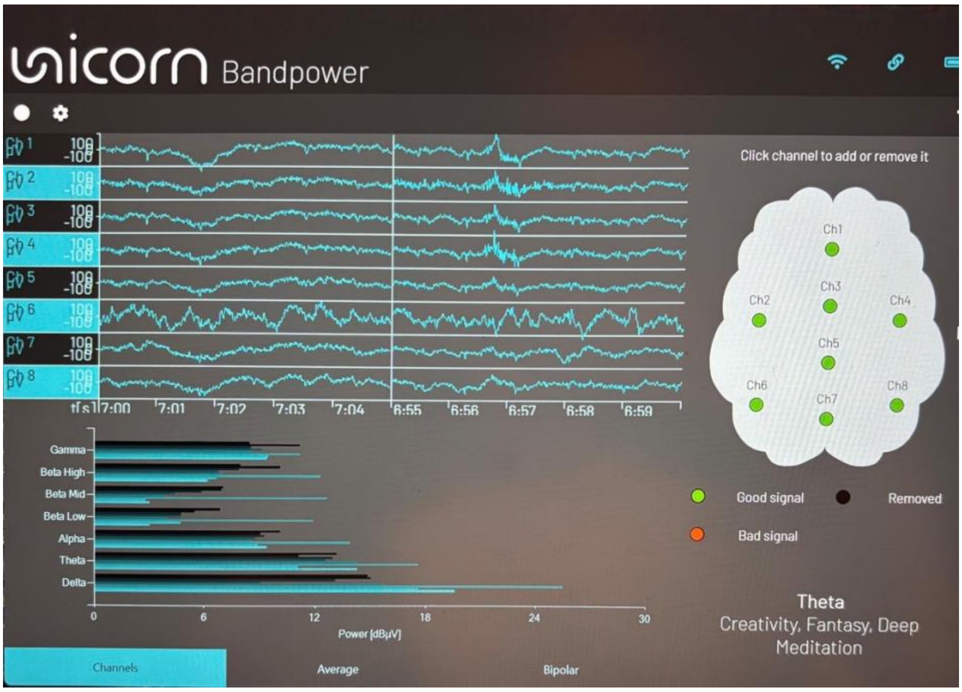

Figure 12 - Preview of Active Bandpower in the Unicorn Software

Cognitive Task


Figure 13 - Example of the card sorting task

To ensure participants remained engaged and to provide a consistent cognitive baseline, a simple card-sorting task was chosen. Figure 13 shows the card sorting procedure. The task involved a stack of cards numbered 1-15. Participants were instructed to continuously sort the cards, starting in ascending order (1-15) and then in descending order (15-1), until the one-minute exposure period was done. Similair done in the research of (Zocchi & Kitsantas, 2023)

Subjective rating instruments
The subjective data were collected using two instruments. The first instrument was the post-scenario Likert scales: a 3-item questionnaire done after each lighting scenario, measuring arousal, valence, and task difficulty on a 7-point Likert scale. After the four scenarios were over, there was a post-experiment comparative questionnaire, the second instrument used to measure subjective data: a 4-item questionnaire taken to ask the participants to identify which scenario(s) caused the most noticeable flicker, visual discomfort, negative emotional response, and task difficulty.

The questions asked:

1. *On a scale of 1 to 7, how **calming or stimulating** was the flickering light?"*
   1 being very calming and 7 being very stimulating

2. *On a scale of 1 to 7, how much did the **lighting** make it more difficult to sort the cards?"*
   1 being very unpleasant and 7 being very pleasant.

3. *On a scale of 1 to 7, how much did the **lighting** make it more difficult to sort the cards?"*
   1 being not difficult and 7 being very difficult

Experimental Design
The study works with a 2x2 within-subject repeated measures design. All participants were exposed to all four experimental conditions, presented in a counterbalanced order to minimize learning or fatigue effects.

Independent Variables for this experiment are 200Hz and 60Hz, as well as the Luminaire Position, making that there are four resulting scenarios.

Independent variable 1: Luminance flicker frequency with two levels: 200Hz and 60Hz.
Independent Variable 2: Luminaire position, with two levels: general and task.

These levels were combined to create four experimental scenarios:
Scenario A: General lighting at 200Hz
Scenario B: Task Lighting at 60Hz
Scenario C: Task Lighting at 200Hz
Scenario D: General Lighting at 60Hz

There are three dependent variables:
1. Subjective ratings: arousal, valence, and task difficulty scores (scale 1-7)
2. Comparative choices: scenarios selected for flicker, discomfort, valence, and difficulty.

3. Objective EEG Data: Mean average power of alpha, beta (low, mid, and high), and gamma frequency bands.

Procedure

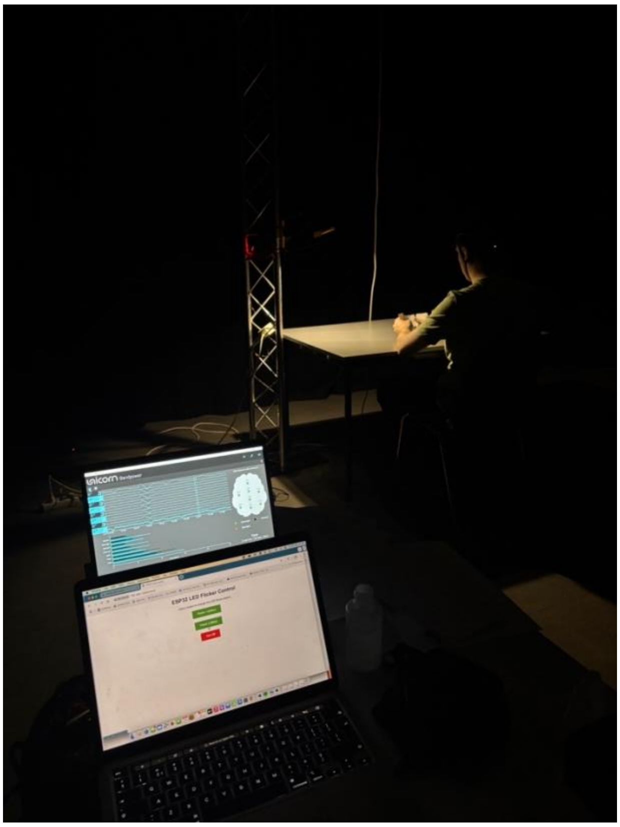

Figure 14 - Researcher View During Experiment

Upon arrival at the light lab, each participant followed a standardized procedure:

1. Informed consent and demographics: participants were briefed on the study and signed an informed consent form (appendix 12), followed by the completion of the pre-experiment demographic questionnaire (appendix 11).
2. When arriving in the light lab, the participants were walked through the experiment, emphasizing that if they experienced discomfort, we would stop the experiment. But also walking them through the steps, one minute of light exposure, followed by 3 Likert scale-based questions.
3. EEG headset fitting: the Unicorn Hybrid EEG headset was fitted to the participant, and the signal quality was checked to ensure accurate data recording. To ensure good signal quality, a water-based gel was applied to the scalp of the participants.
4. Task instructions: The card-sorting task was explained to the participant.
5. Experimental assessments: The participant completed four experimental assessments. Each section consisted of:
    a. A one-minute exposure to one of the four lighting assessments, during which they performed the card-sorting task while their EEG was recorded.
    b. Immediate completion of the 3-item post-scenario questionnaire (arousal, valence, and difficulty)

6. Post-experiment comparison: after all four assessments were completed, the participants answered the 4-item comparative questionnaire.
7. Debriefing: the EEG headset was removed, and the participant was thanked for their time.

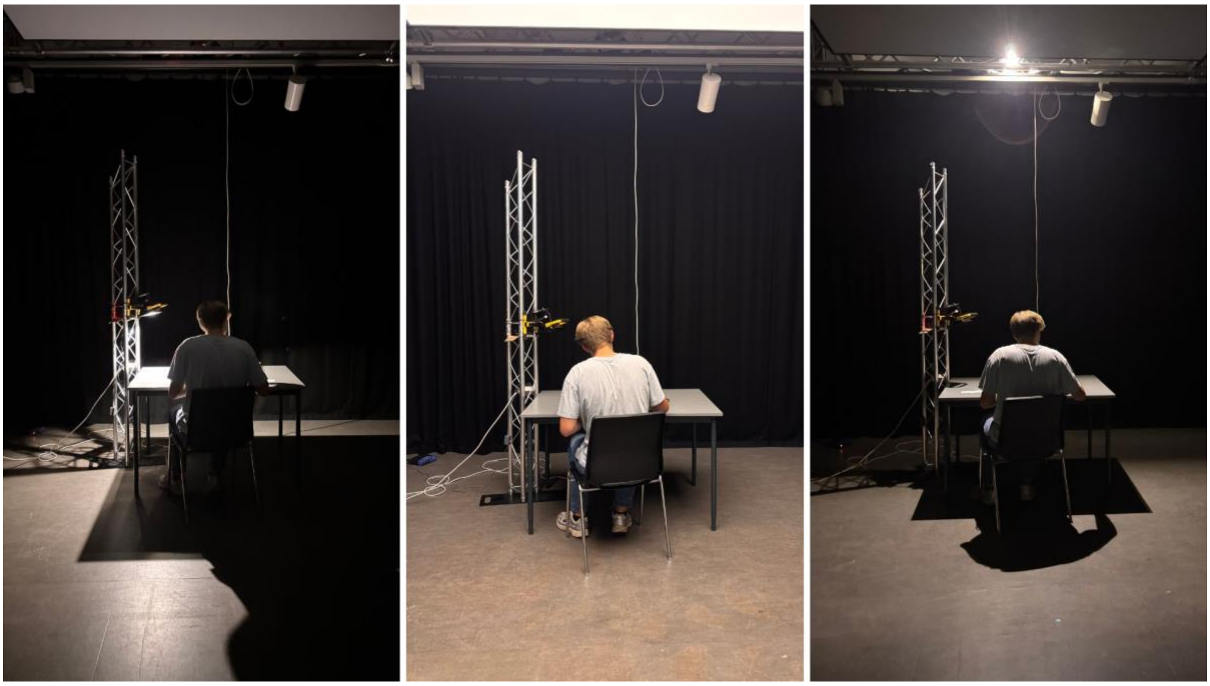

Figure 15 - Example of the experiment: left, Task Lighting; middle, Neutral lighting between tests; right, General Lighting

Data processing and Analysis

Each participant was numbered, going from p01 to p016 (with p02 not having EEG data), based on their time and date of testing. All the data gathered during the experiment were digitized and compiled into a master data file, which aligned with the corresponding participant's ID and scenario.

EEG Data
The EEG data exported from the Unicorn Suite as CSV files contained all the bandpower information. The data structure for each file consists of 70 columns, representing 7 frequency bands (Delta, Theta, Alpha, Beta Low, Beta Mid, Beta High, and Gamma) for each of the 8 EEG channels. Columns 1-56 represent the bandpower, columns 57-63 are the averages of these bands over all 8 channels. Columns 65-70 correspond to the bandpower computed on all bipolar directions of the channels, averaged per band. The bandpower features are updated at 25Hz; if any channel is disabled or non-functional, the value is noted as NaN. No motion artifact rejection was performed on the bandpower data.

For each one-minute recording, the mean average was calculated for each individual bandpower metric (e.g., Alpha_Channel_1, Beta_Low_Channel_1, etc). These detailed averages were used to create the final datasets, including a master summary and a simplified table with a single averaged value for the alpha, beta, and gamma bands for each participant per scenario.

Analysis of the hypothesis

Main Goal: To provide evidence-based recommendations for lighting designers.
RQ: How do a luminaire's flicker frequency (60 Hz vs. 200 Hz) and spatial position (general vs. task lighting) impact perceived comfort and **cognitive load**, and what are the corresponding effects on neural activity as measured by EEG?

Based on the research objectives, this study will test three primary hypotheses. These hypotheses address the effects of luminaire position and flicker frequency and the relationship between subjective perception and objective neurophysiological data. An often-occurring problem within design and science, with this hypothesis, the goal is to bridge the gap.

For each data set the Mean and the Sample Standard Deviation will be calculated. The following equation will be applied in the calculation.
Calculating the Mean:

$$\text{Mean}(\bar{x}) = \frac{\text{Sum of all values}}{\text{Number of values}} = \frac{\sum_{i=1}^{n} x_i}{n}$$

x_i = each individual value

n = number of values

Calculating the Sample Standard Deviation

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

x_i = each value

$\bar{x}$ = mean of the dataset

n = number of values

For data analysis, the raw EEG data were first summarized by calculating the mean power for the alpha, beta, and gamma frequency bands for each participant under each experimental scenario. Subsequent statistical analysis, specifically paired t-tests, was conducted using GraphPad Prism software. All figures were generated using the visualization tool Fabi.Ai (Marc Dupuis & Lei Tang) (GraphPad)

Hypothesis 1: The effect of luminaire position

This hypothesis investigates the primary research question regarding the influence of a This hypothesis investigates the primary research question regarding the influence of a luminaire's spatial position on user perception.

To test the primary hypothesis that luminaire position significantly impacts perception and cognitive focus, a targeted analytical approach will be employed. This approach is designed to isolate the effect of position (Task vs. General) by comparing scenarios where the flicker frequency was held constant. Based on an initial assessment confirming the normal distribution of the data, parametric statistical tests were selected for all comparisons.

The null and alternative hypotheses for this analysis are:

- **HA**: Task lighting, positioned in the peripheral visual field, will cause a higher reported task difficulty and a greater change in neural activity associated with focus (Gamma power) than general lighting positioned centrally.
- **H0**: There is no significant difference in perception or neural activity between task lighting and general lighting positions.

  Two sets of pairwise comparisons were conducted to test this hypothesis:

1. **High-Frequency Comparison:** Scenario A (General, 200Hz) vs. Scenario C (Task, 200Hz).
2. **Low-Frequency Comparison:** Scenario D (General, 60Hz) vs. Scenario B (Task, 60Hz).

Analytical approach: To test this hypothesis, data will be grouped by flicker frequency. The two high frequency lighting conditions (Scenario A: 200 Hz, Scenario C: 200 Hz) will be combined into a "High-Frequency" group, and the two low frequency lighting conditions (Scenario B: 60 Hz, Scenario D: 60 Hz) will form a "Low-Frequency" group. A comparison of the mean scores for task difficulty will be conducted between these two groups. A similar comparison will be performed on the objective Gamma EEG data to determine if bandpower associated with cognitive load or stress is significantly higher for the Task group.

Analysis of Subjective Perception (Task Difficulty)
To assess the impact on perceived cognitive load, the Likert scale ratings for **Task Difficulty** were compared between the relevant pairs.

- **Statistical Test:** A **paired-samples t-test** was performed for each pair (A vs. C and D vs. B). This test compares the mean score for Task Difficulty between the two related conditions to determine if the difference is statistically significant.
- **Interpretation:** A statistically significant result ($p < 0.05$) would indicate that participants' reported difficulty in sorting the cards was significantly different between the general and task lighting positions, thus supporting the alternative hypothesis (HA).

Analysis of Objective Neural Activity (Gamma Power)

To investigate the physiological correlate of focus, the averaged **EEG Gamma power** was compared between the same pairs of scenarios. Gamma waves are often associated with higher-level cognitive functions and focus, and a change in their power could indicate a difference in the cognitive effort required to perform the task.

Statistical Test: A **paired-samples t-test** was conducted for each pair (A vs. C and D vs. B). This test compares the mean Gamma power between the two related conditions to determine if there is a statistically significant difference.

Interpretation: A significant result ($p < 0.05$), particularly if Gamma power were higher in the task lighting conditions, would suggest that the peripheral luminaire demanded greater cognitive resources to maintain focus on the central task. This would provide objective evidence in support of the alternative hypothesis (HA). Subjective data analysis (task difficulty), A and scenario C as a statistical test.

To test the hypothesis that task lighting (peripheral) is perceived as more difficult than general lighting (ceiling), the subjective Task Difficulty ratings were analyzed using paired-samples t- tests. The analysis was done separately for the high-frequency (200Hz) and low-frequency (60Hz) conditions to isolate the effect of luminaire position.

Hypothesis 2: The effect of flicker frequency

This hypothesis addresses how different flicker frequencies impact user comfort and perception. The null and alternative hypotheses for this analysis are:

- **HA**: Lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort than lighting at 200 Hz.
- **H0**: There will be no significant difference in task difficulty and neural activity (Gamma power) between 60 Hz and 200 Hz lighting.

Two sets of pairwise comparisons were conducted:

1. **Task Lighting Comparison:** Scenario C (Task, 200Hz) vs. Scenario B (Task, 60Hz).
2. **General Lighting Comparison:** Scenario A (General, 200Hz) vs. Scenario D (General, 60Hz).

Analytical approach: To test this hypothesis, data will be grouped by luminaire position. The two general lighting conditions (Scenario A: 200 Hz, Scenario D: 60 Hz) will be combined into a "General" group, and the two task lighting conditions (Scenario B: 60 Hz, Scenario C: 200 Hz) will form a "Task" group. A comparison of the mean scores for task difficulty will be conducted between these two groups. A similar comparison will be performed on the objective Gamma EEG data to determine if bandpower associated with cognitive load or stress is significantly higher for the Task group.

Analysis of Subjective Perception (Task Difficulty)

To assess the impact on perceived cognitive load, the Likert scale ratings for **Task Difficulty** were compared between the relevant pairs.

- **Statistical Test:** A **paired-samples t-test** was performed for each pair (A vs. D and B vs. C). This test compares the mean score for Task Difficulty between the two related conditions to determine if the difference is statistically significant.
- **Interpretation:** A statistically significant result ($p < 0.05$) would indicate that participants' reported difficulty in sorting the cards was significantly different between the 60Hz and 200Hz lighting frequencies, thus supporting the alternative hypothesis (HA).

Analysis of Objective Neural Activity (Gamma Power)

To investigate the physiological correlate of focus, the averaged **EEG Gamma power** was compared between the same pairs of scenarios. Gamma waves are often associated with higher-level cognitive functions and focus, and a change in their power could indicate a difference in the cognitive effort required to perform the task.

- **Statistical Test:** A **paired-samples t-test** was conducted for each pair (A vs. D and B vs. C). This test compares the mean Gamma power between the two related conditions to determine if there is a statistically significant difference.
- **Interpretation:** A significant result ($p < 0.05$), particularly if Gamma power were higher in the 60 Hz lighting conditions, would suggest that the peripheral light source demanded greater cognitive resources to maintain focus on the central task. This would provide objective evidence in support of the alternative hypothesis (HA).

This analysis investigated Hypothesis 2, which posits that lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort compared to lighting at 200 Hz. The effect of flicker frequency was examined by comparing scenarios where the luminaire position was held constant. Based on the normal distribution of data, paired-samples t-tests were employed for all comparisons.

Hypothesis 3: Correlation between subjective and objective measures

This hypothesis addresses the link between perceived experience and physiological response, validating the correlation between subjective and objective measures.

- **HA**: There will be a positive correlation between subjectively reported task difficulty or discomfort and objectively measured EEG bandpower indicative of cognitive load or stress.
- **H0**: There will be no significant correlation between self-reported scores and EEG measurements.

Analytical Approach: A correlation analysis will be performed. For each participant and each of the four scenarios, the subjective Likert scale score for a given metric (e.g., task difficulty) will be paired with the corresponding objective EEG metric (e.g., average bandpower). A statistical test will then determine the strength and significance of the correlation between these paired subjective and objective data points.

The correlation heatmaps visualize the correlation matrix. These heatmaps are the ideal visualization for understanding the link between subjective and objective measures, as they directly show the Pearson's r correlation coefficient between every pair of these variables.

Each cell shows the correlation coefficient between two variables, between a range from -1 to +1. The closer to +1 (red) represents a strong positive correlation. As one variable increases, the other tends to increase. Close to -1 (blue) shows a strong negative correlation. As one variable increases, the other tends to decrease. In the middle, close to 0 (white), stating a weak or no correlation, the variables do not appear to be related.

For this hypothesis, the interest is in the cells where the "difficulty" row intersects with the EEG columns (alpha, beta, and gamma). Each scenario we be individually investigated, and visualizing all four scenarios will create confusion in the overload of data.

By answering these hypotheses, the aim is to be able to answer the main research question:

How do flicker frequencies, 60 and 200 Hz, and luminaire position, general and task lighting, influence human comfort and cognitive performance, as measured by both subjective ratings, Likert scale, and objective EEG data?

Results

This chapter shows the data collection and statistical analysis done during the experiment. The findings and results are organized to systematically address the hypotheses. The chapter starts with a summary of the participants' demographics and descriptive statistics for all measured variables. After that, the findings from the pairwise comparisons for Hypothesis 1 (Position Effect) and Hypothesis 2 (Frequency Effect), followed by the correlation analysis for Hypothesis 3 (Subject-Objective Link), will be explained. Lastly, there will be an elaboration on the individual trajectory plots. All statistical tests were conducted with a significance level of $\alpha = 0.05$

Descriptive Statistics

Participant Demographics

In the study, a total of 16 individuals participated; however, the data from participant (p02) has been excluded from the EEG data due to unusable recordings. This results in a final sample of n=15 for all analyses. The sample consisted of 9 females and 6 males. The mean age of the participants was 24.5 years (Standard Deviation = 2.1 years). The group was predominantly right-handed, with 13 right-handed participants and 2 left-handed participants. A majority of the participants reported having a visual impairment. With 9 participants using glasses, contacts for conditions such as myopia and astigmatism.

Individual Participant Trajectories

The examination of the individual participant trajectory plot reveals the nuances in responses to the different lighting scenarios that are not apparent from the aggregated group data.
The graphics are split into subjective data and objective data.

Figures 16, 17 and 18 visualize the subjective data. Focusing on figure 18, it shows that with the participants who got tested, there is a wide diversity in ratings on task difficulty.

Subjective Data Trajectory Plot

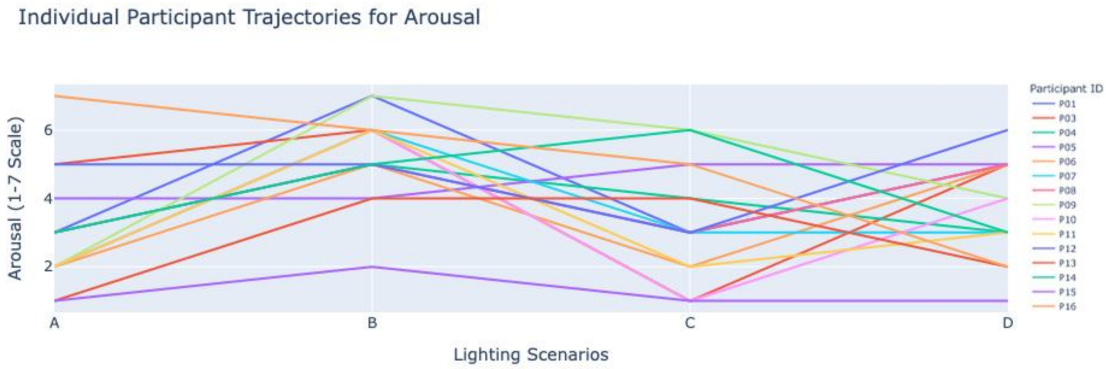

Figure 16 - Individual Participant Trajectories for Arousal

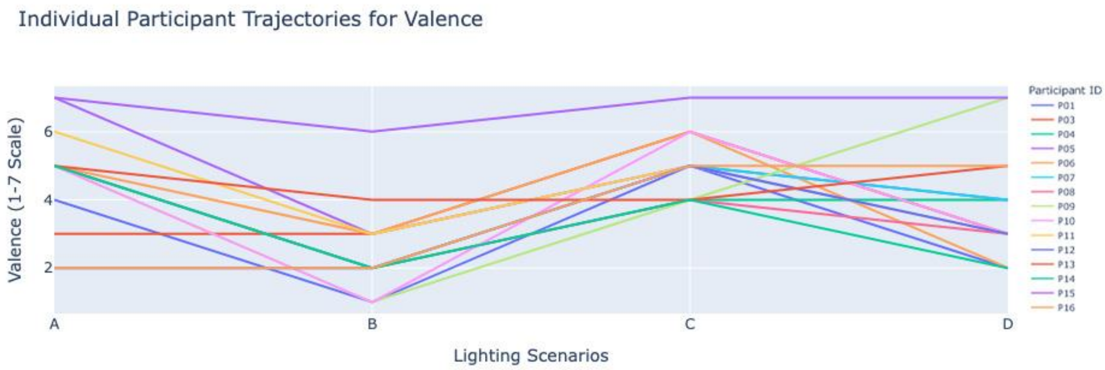

Figure 17 - Individual Participant Trajectories for Valence

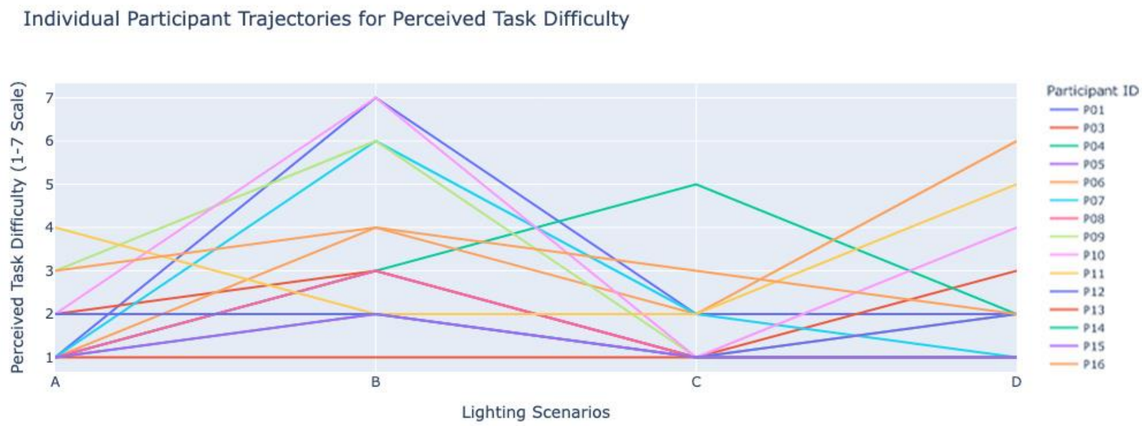

Figure 18 - Individual Participant Trajectories for Perceived Task Difficulty

Trajectory plots were generated for each subjective measure (Arousal, Valence and Task Difficulty) to investigate the consistency of perceptual responses across the participant group. As illustrated in figures 16, 17, and 18, these visualizations show the degree of inter-participant variability in response to the four lighting scenarios.

Objective Data Trajectory Plot

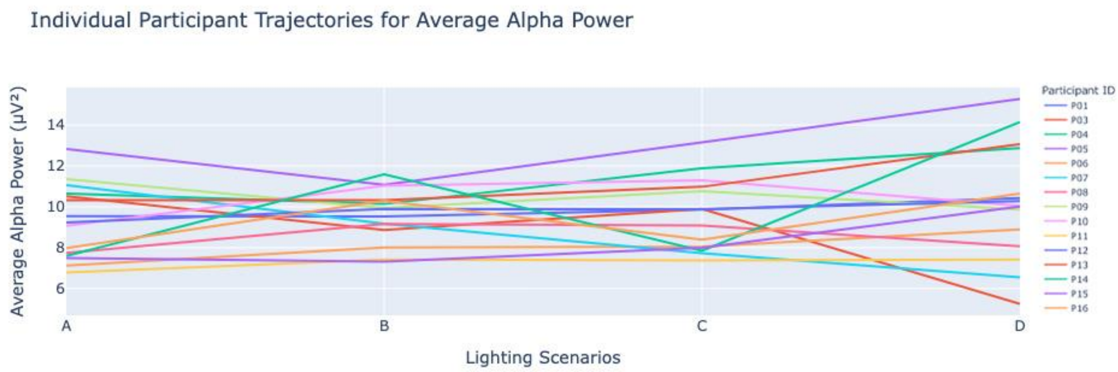

Figure 19 - Individual Participant Trajectories for Average Alpha Power

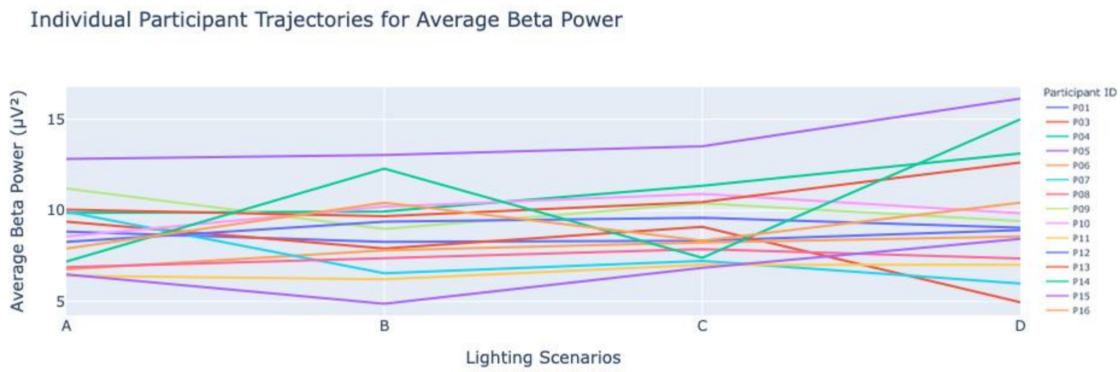

Figure 20 - Individual Participant Trajectories for Average Beta Power

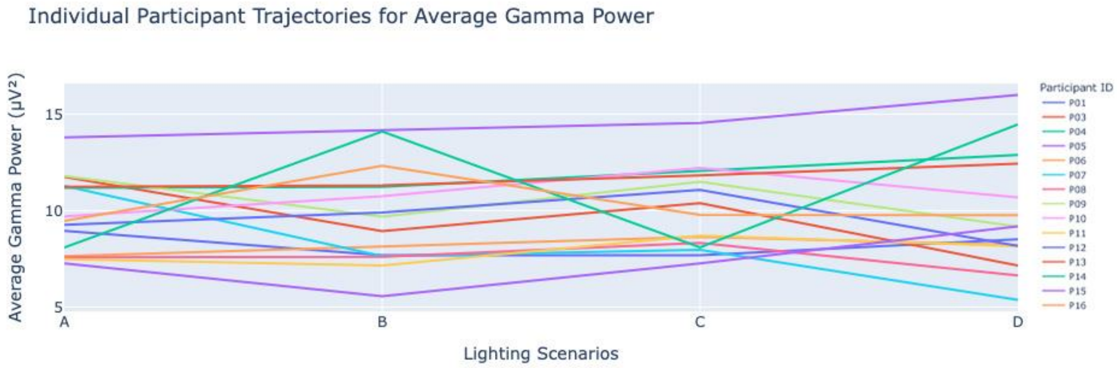

Figure 21 - Individual Participant Trajectories for Average Gamma Power

To explore the individual physiological responses further, as illustrated in Figures 19, 20 and 21, trajectory plots were generated for each averaged EEG bandpower (Alpha, Beta and Gamma). What the visualizations show is the inter-participant variability and the individual consistency of bandpower across the four scenarios.
Some participants demonstrate a substantial fluctuation across the different scenarios in their EEG bandpower, which indicates a considerable physiological sensitivity or reactivity to the changing lighting conditions. Other participants maintain more of a consistent bandpower, suggesting a more stable or less reactive physiological baseline.

Summary of Measured Variables

In Table 1 all the subjective and objective dependent variables across the four scenarios are presented with the mean (M) and standard deviation (SD). This overview provides a summary of the central tendencies and variability of the participants' responses to each lighting condition.

Table 2 - Summary of Measured Variables during Experiment

Measure	**Scenario A (General, 200Hz)**	**Scenario B (Task, 60Hz)**	**Scenario C (Task, 200Hz)**	**Scenario D (General, 60Hz)**
	M (SD)	M (SD)	M (SD)	M (SD)
Subjective Ratings (1-7 Scale)				
Arousal	3.00 (1.65)	5.27 (1.27)	3.27 (1.71)	3.73 (1.43)
Valence	4.73 (1.51)	2.47 (1.30)	5.00 (0.93)	3.80 (1.60)
Task Difficulty	1.67 (0.98)	3.67 (1.95)	1.67 (1.11)	2.33 (1.54)
Objective EEG Data (µV2)				
Average Alpha Power	9.29 (1.79)	9.58 (1.28)	9.61 (1.74)	10.19 (2.79)
Average Beta Power	8.71 (1.87)	8.87 (2.21)	9.11 (1.90)	9.79 (3.20)
Average Gamma Power	9.76 (1.99)	9.75 (2.56)	10.01 (2.13)	9.79 (2.98)

Hypotheses Findings

In figure 22, the EEG bandpower distribution is shown across all lighting scenarios. It shows that there are differences, mainly in the height of the Gamma Bandpower across scenarios.

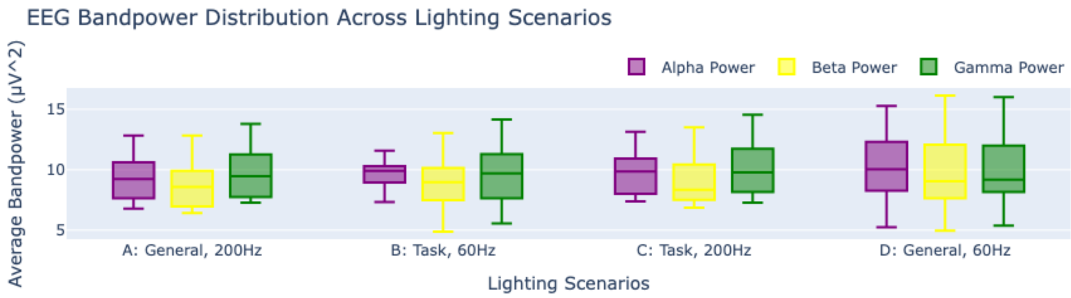

Figure 22 - EEG Bandpower Distribution Across Lighting Scenarios

Hypothesis 1: The effect of luminaire position

This hypothesis investigates the primary research question regarding the influence of a luminaire's spatial position on user perception.

To test the primary hypothesis that luminaire position significantly impacts perception and cognitive focus, a targeted analytical approach was employed. This approach was designed to isolate the effect of position (Task vs. General) by comparing scenarios where the flicker frequency was held constant. Based on an initial assessment confirming the normal distribution of the data, parametric statistical tests were selected for all comparisons.

To test the hypothesis that task lighting (peripheral) is perceived as more difficult than general lighting (ceiling), the subjective Task Difficulty ratings were analysed using paired-samples t-tests. The analysis was done separately for the high-frequency (200Hz), see figure 23, and low-frequency (60Hz), see figure 24, conditions to isolate the effect of luminaire position. All analyses were performed on the final sample of n=15.

Analysis of Subjective Perception (Task Difficulty)

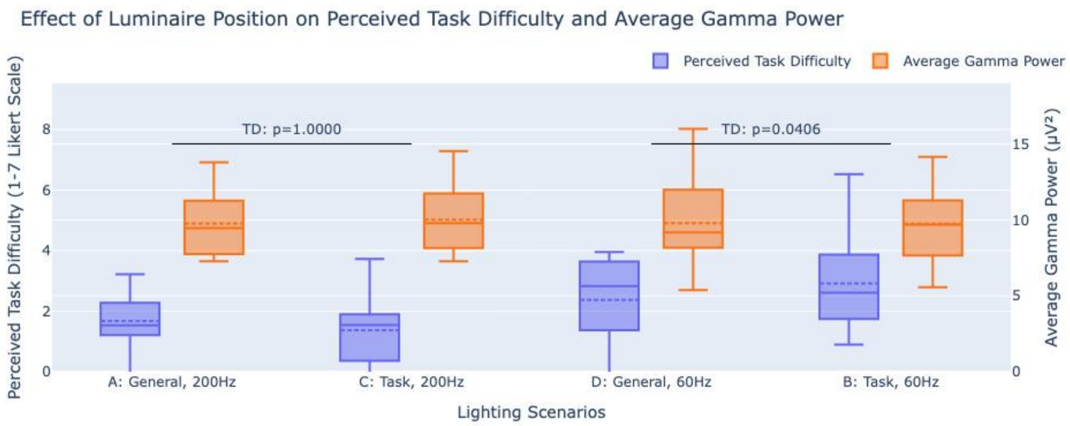

Figure 23 - Effect of Luminaire Position on Perceived Task Difficulty and Average Gamma Power

Comparison of Scenario A and Scenario C (200Hz)

A paired-samples t-test was carried out to compare the Task Difficulty scores between Scenario A (General, 200Hz) and Scenario C (Task, 200Hz). The analysis revealed no statistically significant difference between the two conditions. Participants reported an identical mean difficulty score for both Scenario A (M = 1.67, SD = 0.98) and Scenario C (M = 1.67, SD = 1.11). The statistical result, $t(14) = 0.00$, $p = 1.00$, indicates that when the light source was stable and flicker-free, the position of the luminaire had no measurable effect on the perceived difficulty of the task.

Comparison of Scenario B and Scenario D (60Hz)

A second paired-samples t-test was examined to compare the Task Difficulty scores between Scenario D (General, 60Hz) and Scenario B (Task, 60Hz).

Participants reported a higher mean Task Difficulty for the peripheral Scenario B (M = 3.67, SD = 1.95) compared to the central Scenario D (M = 2.33, SD = 1.54). This provides us with a statistical significance, $t(14) = 2.2563$, $p = 0.0406$.

Analysis of Objective Neural Activity (Gamma Power)

To investigate the physiological correlate of focus, the averaged EEG Gamma power was compared between task and general lighting positions. Gamma waves are often associated with higher-level cognitive functions, and a change in their power could indicate a difference in the cognitive effort required to perform the task. Paired-samples t-tests were performed here as well to analyze these differences.

High-Frequency Condition (200Hz)

A paired-samples t-test was conducted to compare the mean Gamma power between Scenario A (General, 200Hz) and Scenario C (Task, 200Hz). The analysis revealed no statistically significant difference in Gamma activity between the two conditions, $t(15) = 0.66$, $p = 0.52$.

Although not statistically significant, the mean Gamma power was slightly higher in the Task lighting condition (Scenario C) (M = 10.01) compared to the General lighting condition (M = 9.76). This subtle increase could suggest that even in a stable lighting environment, a peripheral light source may require a minor, though not significant, increase in cognitive resources to maintain focus.

Low-Frequency Condition (60Hz)

A second paired-samples t-test compared the mean Gamma power between Scenario D (General, 60Hz) and Scenario B (Task, 60Hz). The results showed no statistically significant difference in Gamma power between the two positions, $t(14) = 0.09$, $p = 0.93$. The mean Gamma power was nearly identical for both Scenario B (M = 9.75) and Scenario D (M = 9.79).

Hypothesis 2: The effect of flicker frequency

This hypothesis addresses how different flicker frequencies impact user comfort and perception. The null and alternative hypotheses for this analysis are:

- HA: Lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort than lighting at 200 Hz.
- H0: There will be no significant difference in task difficulty and neural activity (Gamma power) between 60 Hz and 200 Hz lighting.

This analysis investigated Hypothesis 2, which posits that lighting at 60 Hz will cause significantly higher task difficulty and visual discomfort compared to lighting at 200 Hz. The effect of flicker frequency was examined by comparing scenarios where the luminaire position was held constant. Based on the normal distribution of data, paired-samples t-tests were employed for all comparisons.

Analysis of Subjective Perception (Task Difficulty)

To assess the impact of flicker frequency on perceived cognitive load, Likert scale ratings for Task Difficulty were analyzed.

Task Lighting Position (Scenario B vs. C):

A paired-samples t-test compared Task Difficulty scores between Scenario C (Task, 200Hz) and Scenario B (Task, 60Hz). A statistically significant difference was found, $t(14) = 3.57$, $p = 0.0031$. Participants reported significantly higher Task Difficulty in Scenario B (Task, 60Hz) (M = 3.67, SD = 1.95) compared to Scenario C (Task, 200Hz) (M = 1.67, SD = 1.19). The 95% confidence interval for the difference in means (0.80 to 3.20) does not include zero, further supporting a significant effect. This provides strong evidence that a 60 Hz flicker, when presented as task lighting, significantly increases the perceived difficulty of the task.

General Lighting Position (Scenario A vs. D):

A paired-samples t-test compared Task Difficulty scores between Scenario A (General, 200Hz) and Scenario D (General, 60Hz). The difference in perceived difficulty did not reach statistical significance, $t(14) = 1.78$, $p = 0.096$. Participants reported a higher mean Task Difficulty for Scenario D (General, 60Hz) (M = 2.33, SD = 1.54) compared to Scenario A (General, 200Hz) (M = 1.67, SD = 0.98).

Analysis of Objective Neural Activity (Gamma Power)

To investigate the physiological correlates of focus, averaged EEG Gamma power was compared across the frequency conditions.

Task Lighting Position (Scenario B vs. C):

A paired-samples t-test compared Gamma power between Scenario B (Task, 60Hz) and Scenario C (Task, 200Hz). No statistically significant difference was found, $t(14) = 0.49$, $p = 0.63$. The mean Gamma power for Scenario B (M = 9.75, SD = 2.56) was very similar to Scenario C (M = 10.01, SD = 2.13), and the 95% confidence interval (-1.38 to 0.87) includes zero. This indicates that flicker frequency, in the task lighting position, did not significantly alter objective measures of cognitive focus as represented by Gamma power.

General Lighting Position (Scenario A vs. D):

A paired-samples t-test compared Gamma power between Scenario A (General, 200Hz) and Scenario D (General, 60Hz). No statistically significant difference was found, $t(14) = 0.03$, $p = 0.98$. The mean Gamma power for Scenario D (M = 9.79, SD = 2.98) was virtually identical to Scenario A (M = 9.76, SD = 1.99), and the 95% confidence interval (-1.60 to 1.65) includes zero. This suggests that flicker frequency in the general lighting position also did not significantly impact objective measures of cognitive focus.

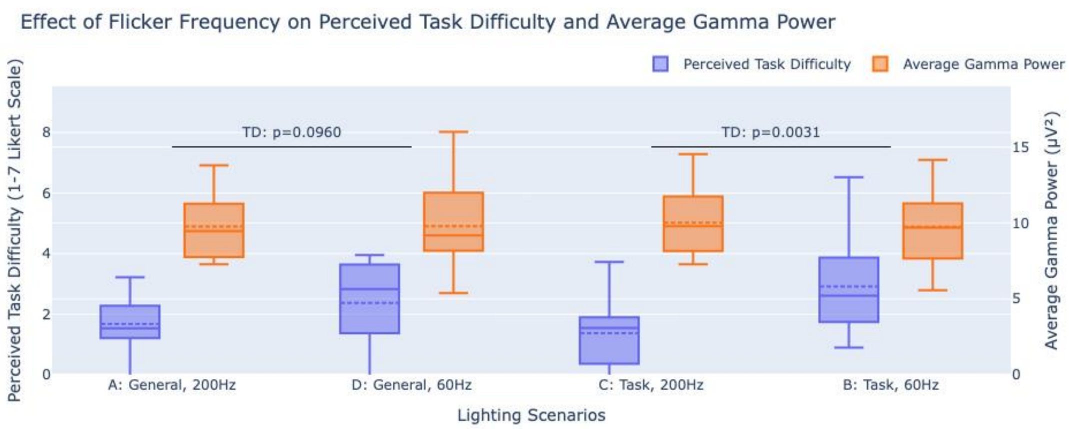

Figure 24 - Effect of Flicker Frequency on Perceived Task Difficulty and Average Gamma Power

Hypothesis 3: Correlation between subjective and objective measures

This hypothesis addresses the link between perceived experience and physiological response, validating the correlation between subjective and objective measures.

- HA: There will be a positive correlation between subjectively reported task difficulty or discomfort and objectively measured EEG bandpower indicative of cognitive load or stress.
- H0: There will be no significant correlation between self-reported scores and EEG measurements.

Correlation matrix per lighting scenario

An overview of the correlation Matrix of all Measures is in figure 25.

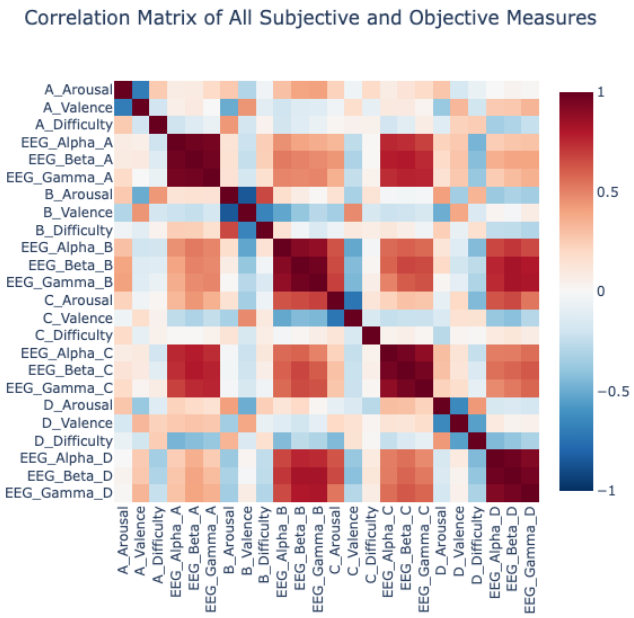

Figure 25 - Correlation Matrix of All Subjective and Objective Measures

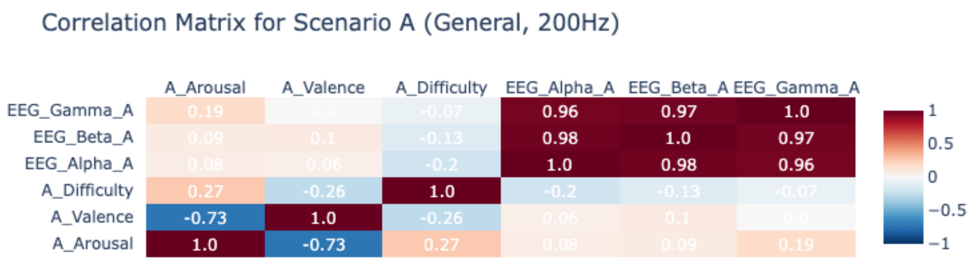

Figure 26 - Correlation Matrix for Scenario A (General, 200Hz)

Scenario A, General Lighting 200Hz, see Figure 26, showcases a very weak correlation between the difficulty and the EEG measures: Alpha (-0.20), Beta (-0.13), and Gamma (-0.07). All these values suggest no meaningful relationship, as they are all close to zero.

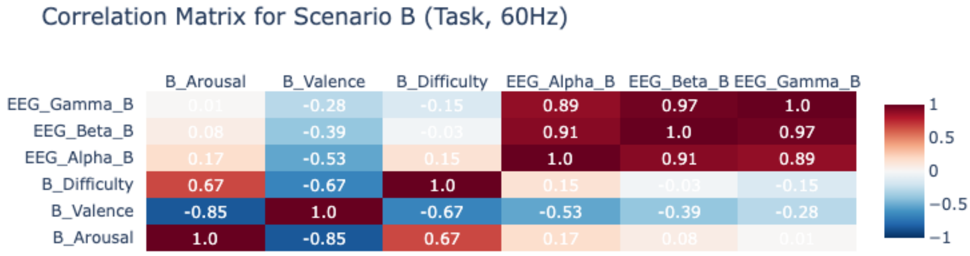

Figure 27 - Correlation Matrix for Scenario B (Task, 60Hz)

In figure 27, Scenario B (Task, 60Hz, weak correlations are seen again, Alpha (-0.05), Beta (0.06), and Gamma (0.02). However a strong correlation between task difficulty and arousal can be noticed.

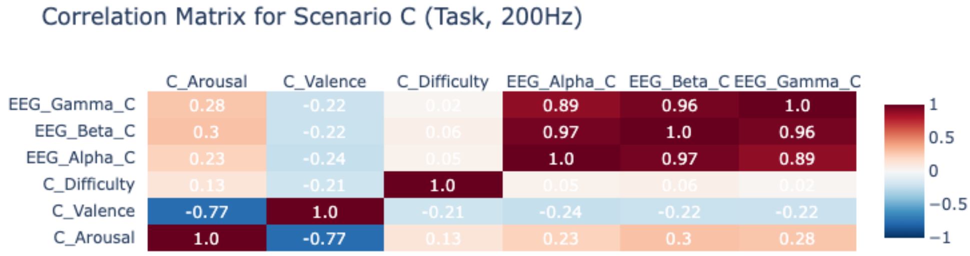

Figure 28 - - Correlation Matrix for Scenario C (Task, 200Hz)

The correlations remain weak: Alpha (0.05), Beta (0.06) and Gamma (0.02) in figure 28, Scenario D (general, 60Hz).

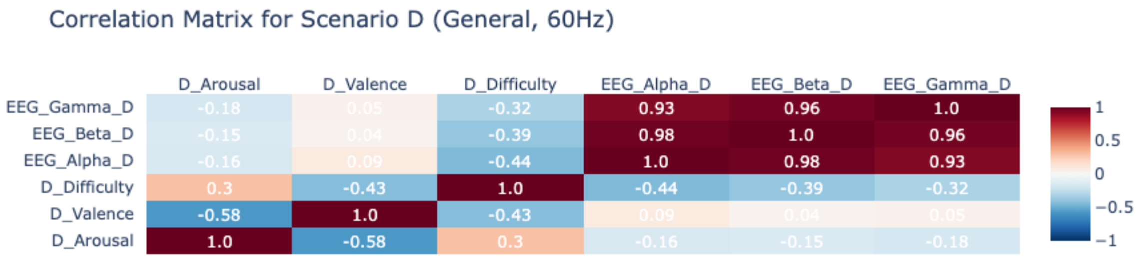

Figure 29 - Correlation Matrix for Scenario D (General, 60Hz)

The most notable relationships are in scenario D, Figure 29, while still being negative and weak to moderate: alpha (0.44), Beta (-0.39), and Gamma (-0.32), While the relationship remains a negative correlation, it is a notable one. The negative correlation is contrary to the hypothesis; it suggests that as task difficulty increased, EEG bandpower tended to decrease.

In this approach, the overall brain behavior link will be assessed across the two different frequencies, from nondisruptive 200Hz to the 60Hz light condition.

A Pearson correlation analysis was performed to test the hypothesis that the perceived experience is correlated with the physiological responses. The initial analysis of the correlation within each scenario showed only weak and non-significant relations. To reveal an underlying trend was difficult with this analytical approach, as the subjective responses within a single condition were often too narrow. This is because the range of subjective responses within a single condition was often too narrow to reveal an underlying trend.

Analysis of 200Hz Scenarios (A and C)

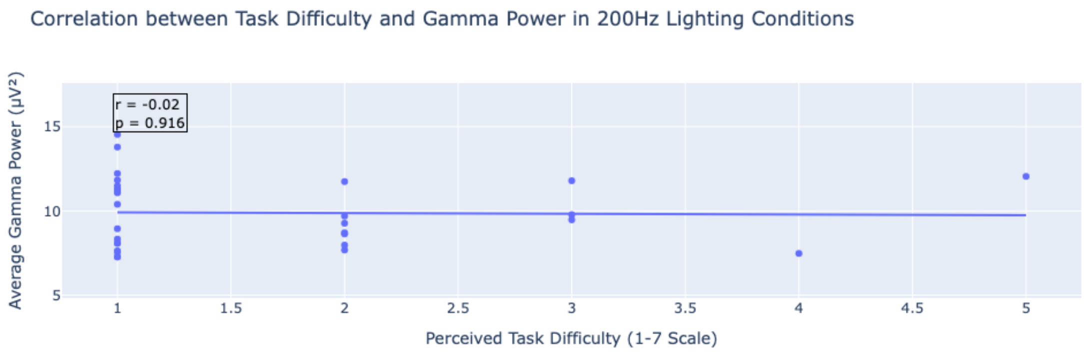

Figure 30 - Correlation between Task Difficulty and Gamma Power in 200Hz Lighting Conditions

The subjective ratings for Task Difficulty from the 200Hz scenarios A and C were combined and analyzed against the corresponding average gamma power, see Figure 30. To assess the relation a Pearson correlation test was performed. The result in figure 30, showed to be not statistically significant (p=0.916).

Analysis for 60Hz Scenarios (B and D)

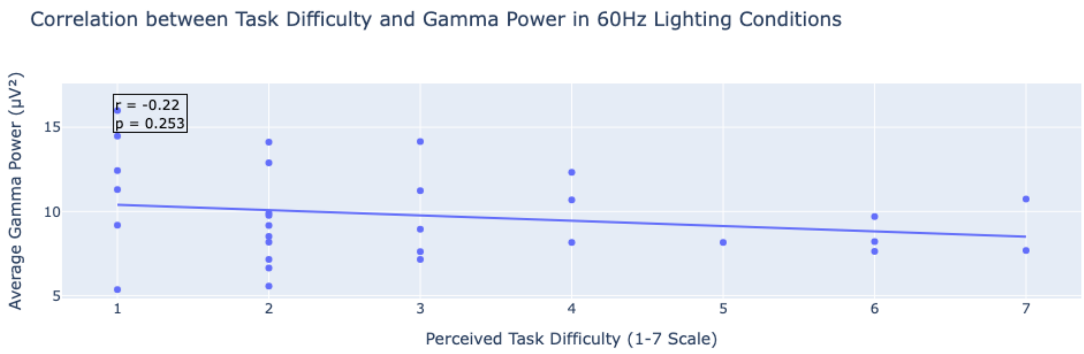

Figure 31 - Correlation between Task Difficulty and Gamma Power in 60Hz Lighting Conditions

The same analysis was performed for the disruptive lighting scenarios with 60Hz, scenario B and D in Figure 31. The combined Task Difficulty ratings were analyzed against the corresponding Average Gamma Power values. The correlation between perceived difficulty and Gamma power was not statistically significant (p=0.253).

Discussion

The aim of this study is to investigate how luminaire's flicker frequency and position impact perceived comfort and cognitive load. By both using subjective ratings and objective EEG measures. In the discussion the key findings will be interpreted in relation to the three primary hypotheses, connecting them to existing research and exploring the practical implication for lighting design.

The most significant finding of this study is the interaction of position and frequency determine the user's experience.

To achieve this, a 2x2 experimental design was employed. With having the Flicker Frequency (200Hz and 60Hz) and Luminaire Position (General and Task) as independent variables. The dependent Variables consist of the subjective measures, measured with the Likert scale, and objective measures, measuring the EEG Bandpower.

Trajectory Plots

While Hypotheses 1 and 2 show significant average differences between the conditions, the trajectory plots for per participant a more nuanced view. An interesting finding is the considerable heterogeneity in subjective responses across the scenarios. Contrary to the expectation that all participants would uniformly rate scenario B (task lighting 60Hz) as highly difficult, the graphic shows a wider distribution of individual ratings.

This finding underscores that while a lighting condition may be disruptive on average, the subjective experience is not rigid. The scattered nature of the individual trajectories suggests that a personal sensitivity to flicker and positional distraction is a notable factor, leading to perceptual outcomes that are diverse even under identical environmental stressors. This aligns with the research of by (Mankowska et al., 2022) who investigated the understanding of how flickering stimuli involve complex neuropsychological mechanisms, and how that can differ between individuals.
It is an interesting finding that a sample group of 15 participants showed such diversity. For future works it would be interesting to employ a larger sample size, not only would it enhance the statistical power and generalizability, it also allows for a more thorough characterization of response diversity across a broader population

Hypotheses 1

Conclusion on Task Difficulty

There is strong evidence for an interaction between flicker and luminaire position based on the results for hypotheses one. During perceived task difficulty, the position of the luminaire became a significant factor; in this case, at 60Hz, the task lighting position. The participants reported a higher mean Task Difficulty for the peripheral 60Hz task lighting ($M = 3.67$, $SD = 1.95$) compared to the 60Hz general lighting ($M = 2.33$, $SD = 1.54$). This provides us with a statistical significance, $t(14) = 2.2563$, $p = 0.0406$.

While with the high-frequency lighting, the luminaire placement seemed to have no effect, it significantly increased task difficulty under the low-frequency condition. The combination of a 60Hz flicker and task (peripheral) luminaire position resulted in the highest difficulty ratings across all scenarios. This finding supports the hypothesis that the negative cognitive impact of poor lighting placement is conditional and is magnified by the presence of flicker.

Conclusion on Gamma Power

Based on the paired t-test analyses, the position of the luminaire (Task vs. General) did not have a statistically significant effect on the average Gamma power in either the 200Hz or 60Hz conditions. Therefore, based on this objective measure alone, we cannot conclude that task lighting required a significantly higher level of cognitive focus than general lighting. This indicates that while participants may have *felt* that the task was more difficult under certain conditions, this was not reflected as a significant change in their Gamma brainwave activity.

Conclusion on Luminaire Position

Concluding, in the first hypothesis it is proposed that the peripheral task lighting would create more disruption than central general lighting. This finding was partially supported, with a critical note; only when 60Hz was present. Under stable, high frequency 200Hz lighting, the luminaire's position had no measurable effect on perceived task difficulty ($p=1.00$). However, having the luminaire position in the peripheral "task" position, under 60Hz flicker, caused a statistically significant increase in perceived difficulty ($p=0.041$).

While a stable light, high frequency, is easy to ignore, the low frequency of 60Hz flicker forces the cognitive system to expend energy suppressing it, which is reflected in the high subjective ratings of task difficult. This finding suggests that the human brain can effectively filter out a constant, stimulus in the peripheral visual field. However, a flicker light source acts as an insistent, distracting signal that captures attentional resources. The neuropsychological mechanisms behind flicker processing can demand attentional resources, especially when the flickering luminaire is in the peripheral field. (Mankowska et al., 2022) (Bullough, Skinner et al., 2013)

A potential cause for Task Lighting being most disruptive, could be the relationship between the distance of a light source and the potential visual discomfort. Another reason could be the physiological characteristics of the participants. The sample group had a fairly young age (average 24.5), research has shown that sensitivity to dim light (mesopic sensitivity) is the highest in young adults and has a significant decrease in older populations. While this is not a directly addressing the sensitivity to task lighting it does support the underlying principle that age is a critical variable in the perception of light. (Moreira-Estebaranz et al., 2022)

To confirm this assumption to the fullest, further future studies should specifically investigate the relationship between age and sensitivity to direct lighting.

Hypothesis 2

Conclusion on Task Difficulty:

The findings show a strong evidence of task difficulty and flicker frequency. A statistical difference was in particular noticeable with the 60Hz frequency positioned in the Task lighting position. The general lighting position however did not suggest a statistical difference however people did report a higher task difficulty for 60Hz frequency compared to 200Hz.

The second hypothesis predicted that 60Hz lighting would cause higher task difficulty compared to 200Hz lighting, this prediction was strongly supported by the subjective data. The 60Hz flicker, in scenario B, task lighting position, was rated as significantly more difficult than the 200Hz lighting in Scenario C. With a significant high result of p=0.0032. Not significant but similar trend was observed even when the light was in the general position p=0.096. These findings are consistent with a large sum of literature on Temporal Light Artifacts (TLAs). The negative effects of flicker are noted in regulations and industry standards, which aim to limit flicker and prevent from unpleasant effects.(Lindén & Dam-Hansen, 2022b)

Conclusion on Gamma Power:

The analysis of the objective data, the neural activity, did not indicate to have a statistically significant effect on EEG Gamma power, the neural correlate of cognitive focus. There is no significant change shown in the comparison between the 60Hz and 200Hz conditions. This objective finding is notable contrasting to the subjective ratings of task difficulty. This suggests that the distraction or discomfort caused by the flicker light did not translate into an increased level of the specific cognitive focus measured by Gamma power.

Conclusion on Frequency Effect

The analysis provides strong evidence that flicker frequency significantly impacts perceived task difficulty, particularly in the task lighting position. Participants reported significantly higher difficulty with 60 Hz task lighting compared to 200 Hz task lighting, directly supporting HA. A similar, though marginally non-significant, trend was observed for general lighting.

However, these significant subjective differences were not mirrored by statistically significant changes in objective Gamma power. While the subjective data clearly indicate that participants *perceive* 60 Hz flicker as more challenging, this was not associated with a measurable increase in high-frequency brain activity linked to active focus or cognitive effort.

The negative effect of 60Hz flicker was statistically only significant in the task lighting position. This confirms hypotheses one, that position of the luminaire is a crucial moderating variable. Reason for the perception could be that when a lamp is positioned farther away, like the general lighting set up, the flickering light reaching the table would have been more diffuse. The greater the distance from surface to luminaire causes inherently a wider light spread and lower illumination, which could have softened the perception of flicker. The result could therefore be that not just the distance or the frequency played a role but also the light distribution.

Studies focusing on glare, the discomfort you can experience from a luminaire, have demonstrated that the position of the light source in a the visual field is a primary factor that influences the perception and discomfort. (Kong et al., 2024)

It is reasonable to infer that the position of the further away placed luminaire, the general lighting set up, can result in changes in the light distribution. Specifically, the more diffuse and wider light spread that created a lower illuminance on the desk could have diminished the perception of flicker and softened the association to discomfort.

Hypothesis 3

By starting at analysing the four different scenarios, the heat maps did not show too much variation. To deepen the understanding of the correlation between subjective and objective another plotting strategy was applied. The data analysis was conducted by grouping the data according to the flicker frequency, the primary experimental variable.

Research has shown that the human brain shows strong EEG responses to flicker in the range of 1-100Hz. This study findings provide clear and practical evidence of this phenomenon. The 60Hz flicker acts as a direct environmental stressor that limited the user's experience and made a simple cognitive task feel substantially harder. As expected, the 200Hz condition, a frequency well above the critical flicker fusion threshold for most observers, served as a stable and comfortable baseline. (HERRMANN, 2001b)

The result showed, however, to be not statistically significant (p=0.916). This indicates that in the 200Hz, non-disruptive light condition, there was no significant linear relationship between the participants' perceived difficulty and measured gamma brainwave activity.
For the disruptive lighting conditions, scenario B and D, the same analysis was performed. The combined task difficulty ratings were analyzed against the corresponding Average Gamma Power values. The correlation between perceived difficulty and Gamma Power did not reveal a statistically significant relationship ($p = 0.253$).

This observation in variation between individual trajectories underscores that brainwave responses are often participant-specific. Influencing variables to these differences can be a multitude of endogenous and exogenous variables that were not controlled or measured during this experiment. For example, daily variations in stress, baseline cognitive state, or even (despite instructions) unconfirmed consumptions of substances like caffeine.
Whereas in the objective trajectory plots, there were some pronounced "jumps", in the subjective data, there is an overall lack of these "jumps" in most individual lines between scenarios. This suggests that for many participants, the physiological changes in these specific EEG bands were relatively subtle in response to the varying lighting conditions.

The third hypothesis is not supported with the data. Since the correlation between subjective and objective data failed to show a statistically significant relationship.

The correlation findings do not support the alternative hypothesis (HA), since the Pearson correlation analysis failed to find a statistically significant correlation. Therefore, the null hypothesis (H0) cannot be rejected.

The most thought-provoking finding is the clear discrepancy between subjective perception and objective physiological measures in this experiment. While the participants clearly felt that 60Hz flicker made the task more difficult, the feeling was not translated into the measurements of their Gamma brainwave activity. This suggests that the mechanisms driving the feeling of cognitive load under flicker may be different from the specific EEG bandpower metrics used. This highlights a potential 'perception vs reality' gap.
The finding reinforces the critical importance of employing a dual-assessment approach in human-centered design research. As demonstrated in this experiment, subjective self-reports and objective physiological data can tell two different parts of the story.

This presents an interesting "perception vs. reality" gap. Across all scenarios, participants reported that 60Hz made the task more difficult, this subjective strain was not reflected as an increase brainwave activity. For this there are several potential interpretations.
It could be that gamma activity, although it is often linked to focus and active problem-solving, was not the right metric. Possibly, the gamma power did not measure the cognitive stat that flicker caused, a follow up study could be to evaluate the other EEG bands. Another reason for the disparity could be that the subjective rating of "difficulty" may have captured an effective response, for example, frustration, more than just the cognitive one.

On the other hand, it could also be that the phenomenon of neural entrainment is another explanation for this discrepancy. Research has shown that the visual cortex, synchronizes with the frequency of an external flickering light through exhibiting steady-state oscillations. In the research it is shown that it has a particularly strong resonance in the Gamma Band. CITE
There, is a probability that the 60Hz flicker induced a powerful sensory-driven Gamma signal in the EEG. This neural response could have covered any more subtle modulation in the Gamma power related to cognitive load, this could be an explanation of the absence of a statistically significant correlation. (HERRMANN, 2001b)

Conclusion on Subjective and Objective relation

The results of hypotheses three do not invalidate the subjective reports. As a lighting designer, a user feeling uncomfortable is a critical design failure, regardless of whether the brainwave activity changes in an expected way. Literature supports that there is a significant effect on the occupant's mood based on the lighting in a workplace and the mood could influence the performance. This reinforces that the principle of human-centered design must always prioritize perceived experience, since it is the user's perception that drives satisfaction and well-being. (Fakhr & MJ, 2018)

Limitations

In order to provide transparency on the research process, it is important to acknowledge the limitations of the study, to essentially contextualize the findings. While this study did provide insights in the effect of flicker and luminaire position, it was limited by constraints related to the experimental setup, methodology and overall research process. In this chapter the limitations will be outlined as a tool to inform the interpretation of the results and to guide for future research.

Limitation related to the experimental equipment.

There was a significant technical challenge in the development of this experimental lighting design system. This impacted the study's scope and precision.

The luminaires that were utilized in this experiment were custom-built. The creation of the flickering luminaire required a substantial investment of time in understanding the electronics and coding. This to create a stable and controllable flicker at the desired frequencies of 60Hz and 200Hz. While ultimately this development phase was successful, it did take up a considerable amount of time from other aspects of the research, such as conducting a pilot study.

While the created luminaires were functional, there was a lack of detailed photometric data and characterization. Due to limitations in time and available measuring tools, key light properties such as the light spread, luminous intensity distribution, and spectral power distribution were not formally measured. Although the conditions of the experiment were kept consistent for all participants, the lack of this detailed photometric data makes exact replication of the study by other researchers more challenging.

Limitations Related to the Research Methodology

The set-up of the methodology was appropriate for the scale of this experiment; however, there are a few limitations that affect the generalizability of the findings.

The study was conducted with a final sample of n=15. This is a relatively small sample group; nevertheless, for the size of this experiment, this sample group was sufficient for the statistical test employed. But a small sample size limits the statistical power and the ability to generalize the findings to a broader population.

The methodological design, while robust for the scale of this thesis, has several limitations that affect the generalizability of the findings. For recruiting the participants, there was no randomized method, making that most participants were recruited through convenience sampling, and although the requirement was age between 18-40, it ended up being relatively homogeneous in terms of age. These results, into demographic factors, such as age, gender differences, and handedness, while observed as trends, cannot be confirmed as statistically significant effects.

Due to an unforeseen scheduling issue with the light lab and logistical constraints, it was not possible to do a preliminary pilot study. For this experiment, a pilot test would have been valuable for refining the experimental procedure. Before the main experiment, potential technical issues with the setup could have been identified, and the subjective questionnaires could have been validated with a small sample group before commencing the full experiment.

Eventually, the light lab was available, and this is where the experiment was held. Although it is necessary to isolate the effects of independent variables, the experiment was conducted in a fully blacked-out controlled laboratory environment. It does not fully replicate the complexity and diversity of a real-world office or residential setting, where multiple light sources, daylight, and other environmental factors are present. While it was good for the isolation of the unrepentant variables, it may limit the direct applicability of the findings to more complex architectural spaces.

Limitations related to the research process.

The execution of the research was also subject to some practical and logistical limitations.

The interdisciplinary nature of the topics, covering light engineering, neuroscience, and human-centered design, presented a solid body of literature. The starting phase of the literature review was therefore broad, and a more targeted focus could have smoothed out the process of developing a concise theoretical framework.

This research was conducted according to a single researcher protocol, making that the entire experimental procedure was done by one individual. From participant greetings and EEG setup to data recording and administering the questionnaires. Not only did this create a demanding schedule it also introduced the potential of minor procedural inconsistencies. With additional assistance, this could have been mitigated.

Despite these limitations, this study successfully established a significant first step in understanding the interaction between flicker and luminaire position. These findings provide a rich basis for future research.

Future Research Directions

The study gives a good impression of the complexity of lighting. Within this experiment the scope was narrowed down to the correlation between position and luminaire. But as structured in the literature review, lighting consists of various parameters. Further research can be done by investigating the relation between the flickering light and intensity, same goes for duration, distribution, and spectrum.

For the illuminance levels there could be an investigation if 60Hz flicker creates disruptive effects under high and low ambient light levels.

For the light spectrum would it be fascinating to see if 2700K, warmer light, or 4000K, cooler light, alter the perception of flickering.

The acute responses were captured in this study during the one-minute exposure periods. A next step could be to create a study with longer exposure durations. This could help to determine if the duration of exposure is a link to decline in cognitive performance over time, and if it could lead to greater visual fatigue.

Another opportunity lies in the expansion of the participant sample. The current study was done with a sample of n=15, with a relatively homogeneous age group, 22-30. It would be interesting to see a replication of this experiment with a larger, more demographically diverse sample. Besides the statistical power it also allows to explore other demographic factors such as occupation and visual impairments. With a main recommendation to investigate the age-related sensitivity. Future studies should specifically investigate age as a variable and compare the responses between young adults, middle-aged individuals, and older populations. This study could reveal whether older individuals, who. May are more sensitive to glare, have a susceptible to the effects of peripheral flicker.

The third hypothesis emphasized on the gap between subjective ratings and objective measures. The observed gap warrants a deeper investigation. The study focused mainly on Gamma power as the indicator of cognitive load, however, other frequency bands are associated with different cognitive states and should be further explored; alpha power, to investigate the potential changes in relaxation, beta power: to assess the concentration, and even theta power; to explore the sustained attention or state of drowsiness.

To validate the physiological measures and to create a more holistic picture of the human responses other physiological measures could be incorporated. Measures such as heart Rate Variability (HRV) and Electrodermal Activity (EDA) could capture the responses of the nervous system. This could provide insights into stress and arousal which would be a great add on to the cognitive data from the EEG.

The 60 Hz flicker outcome may have induced a SSVEP, a phenomenon where the neural oscillations in the visual cortex synchronize with the flicker frequency. A future study could be set up to investigate the strength of this 6 0Hz entrainment to confirm this assumption.

The simple card-sorting task employed in this study provided a cognitive baseline. To have a deeper understanding of the practical implications, future studies should employ a wider range of tasks. It could investigate a reading comprehension to assess the impact of focus and retention. Or a creative problem-solving task to determine if flicker affects higher-order divergent thinking.

This study generated a lot of directionality potentials for the future. It shows that critical thinking will be rewarded by interesting outcomes, and it shows that within the lighting design community a lot of further investigation is required. By building upon the insights of this thesis a truly human-centered approach and a more comprehensive and nuanced approach can be developed in understanding the negative effects of flicker in our built environments.

Conclusion

The core findings of the thesis are synthesized in this chapter to provide a definitive answer to the research question. First, the key results will be summarized, followed by outlining the study's contribution to the field and presenting practical recommendations for lighting designers. It concludes by identifying the limitations and suggestions for future research directions.

Summary of Key Findings

Using a 2x2 experimental design that varied from flicker frequency (60Hz vs 200Hz) and luminaire position (task vs general), this study assessed the perceived task difficulty, the measured subjective ratings, with the EEG measures. The study identified two primary findings regarding the human response to lighting conditions: Subjective discomfort is context dependent, and there is a disconnect between perception and physiology.
Across all analyses, the 60Hz flicker emerged as the key disruptive factor, having a higher reported task difficulty than the high frequency 200Hz condition. Especially when the luminaire was positioned in the task lighting (peripheral) location. This finding supports the first two hypotheses; it confirms that low-frequency flicker increases the task difficulty, and that the luminaire position modulates this. When the luminaire was positioned peripherally, it seemed to heighten the discomfort by creating an increased visual distraction and attentional demands.
Interestingly, while the subjective experiences of the participants revealed a clear and statistically significant difference, the EEG Gamma power did not show corresponding effects. A main finding of the study was the disparity between perceived cognitive load and objective neural measures (EEG gamma power). While the participants did report a subjective high task difficulty, the corresponding changes were not observed in the brain activity. The gap between perception and physiology underscores a critical implication for lighting design: eventually, the user's subjective experience is the ultimate measure of success. Even when there is no neural strain measured, a design that causes discomfort is not successful in a human-centred context.

Answering the Research Question

This thesis aimed to answer the following research question:
How do flicker frequencies, 60 and 200 Hz, and luminaire position, general and task lighting, influence human comfort and cognitive performance, as measured by both subjective ratings, Likert scale, and objective EEG data?

This study shows that the impact of luminaire flicker on user experience is not absolute, but instead determined by a significant interaction between the flicker frequency and the position of the luminaire. The connection of subjective self-reports and the measured objective EEG data confirms that both temporal and spatial factors must be considered in lighting design.

The primary contribution of this thesis is the demonstration that subjective experience is the ultimate measure in human-centered lighting design. By emphasizing the gap between perception and physiology, this research provides evidence that a lighting designer can fail on a perceptual level, causing discomfort, even when objective neural strain is not detected.

Recommendations for Lighting Designers

The first recommendation for lighting designers focuses on the practical application of these findings. If you must use a luminaire with noticeable flicker, prioritize placing it in a general lighting position. Moving the luminaire out of the user's direct peripheral field makes the flicker far less disruptive. For the peripheral task, lighting is it critical to specify high-frequency flicker-free luminaires as it is the location where temporal light modulations are most intensely perceived.
The second recommendation for lighting designers will therefore be, light is more than we measure. Although our objective data indicates a successful design, don't exclude the inclusion of subjective ratings. When you design, look further than regulations, explore the holistic approach that prioritizes perceptual comfort.

Limitations and Future Research

Finally, the study highlights that there is a need for future research, with a larger and more diverse participant sample, and to explore other factors such as age-related sensitivity, visual comfort, and alternative EEG frequency bands. This study focused on the relation between position and frequency, but lighting is more multifaced than that; investigating the color temperature, duration of exposure, and other positions could strengthen the importance of understanding the non-visual effects of lighting.

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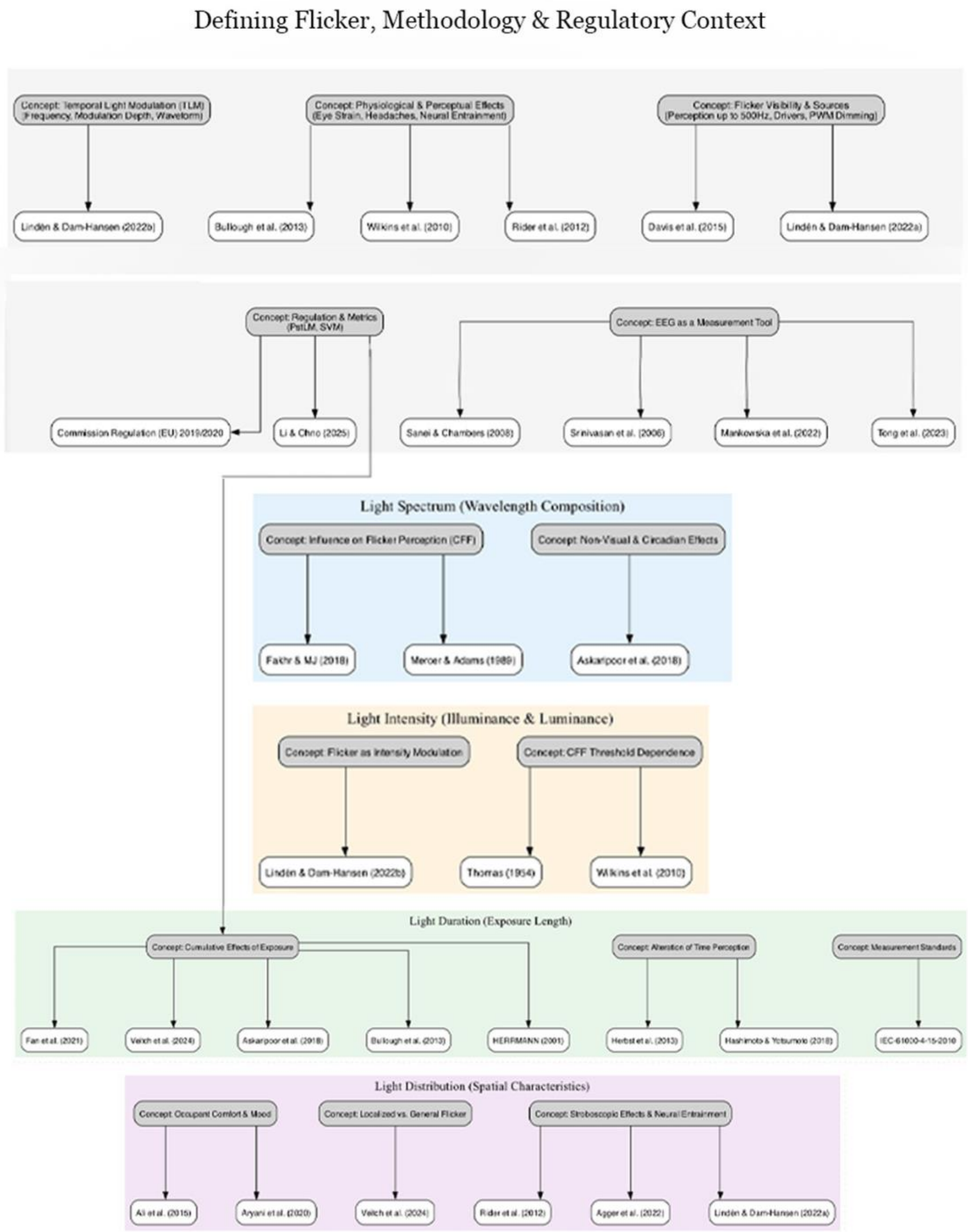
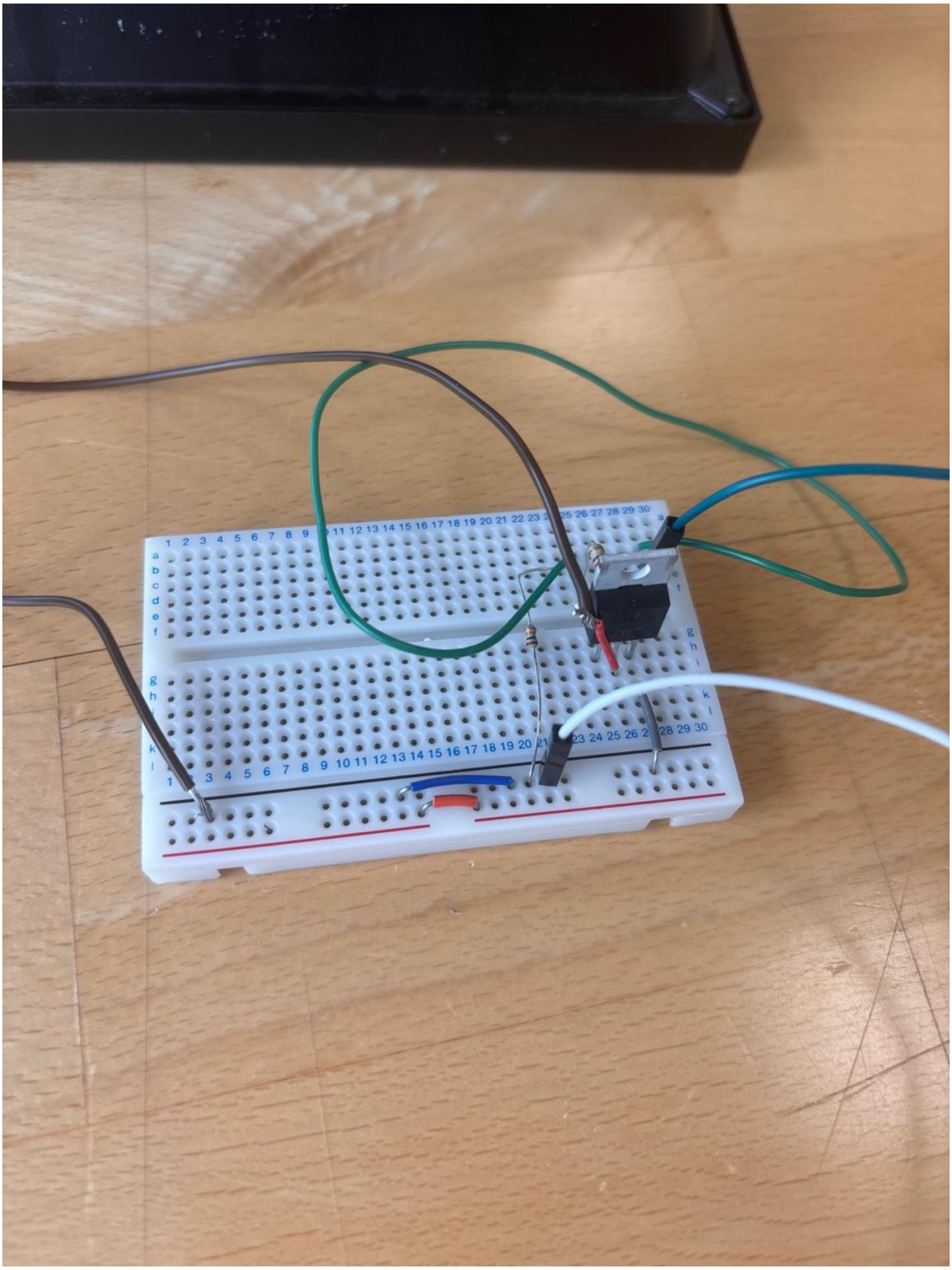
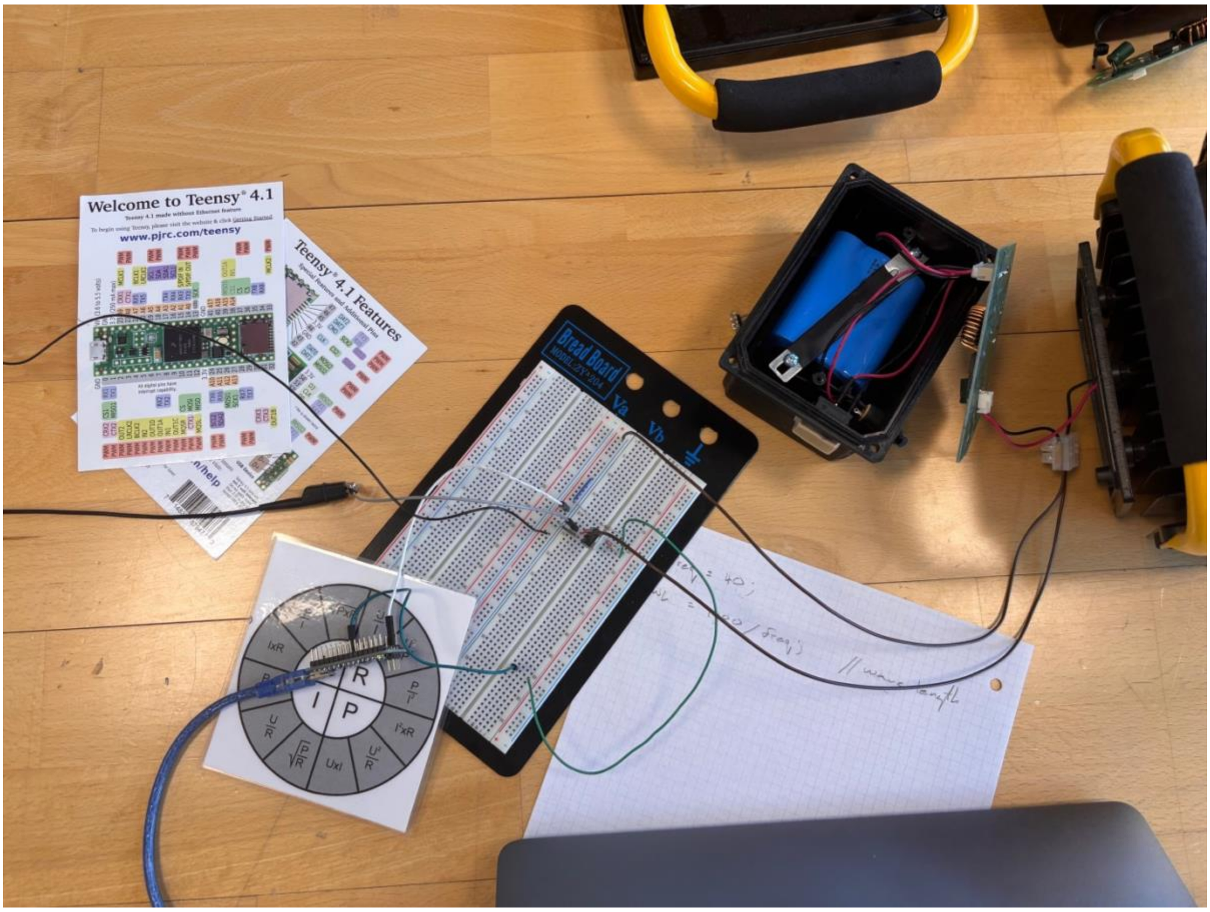
Appendix



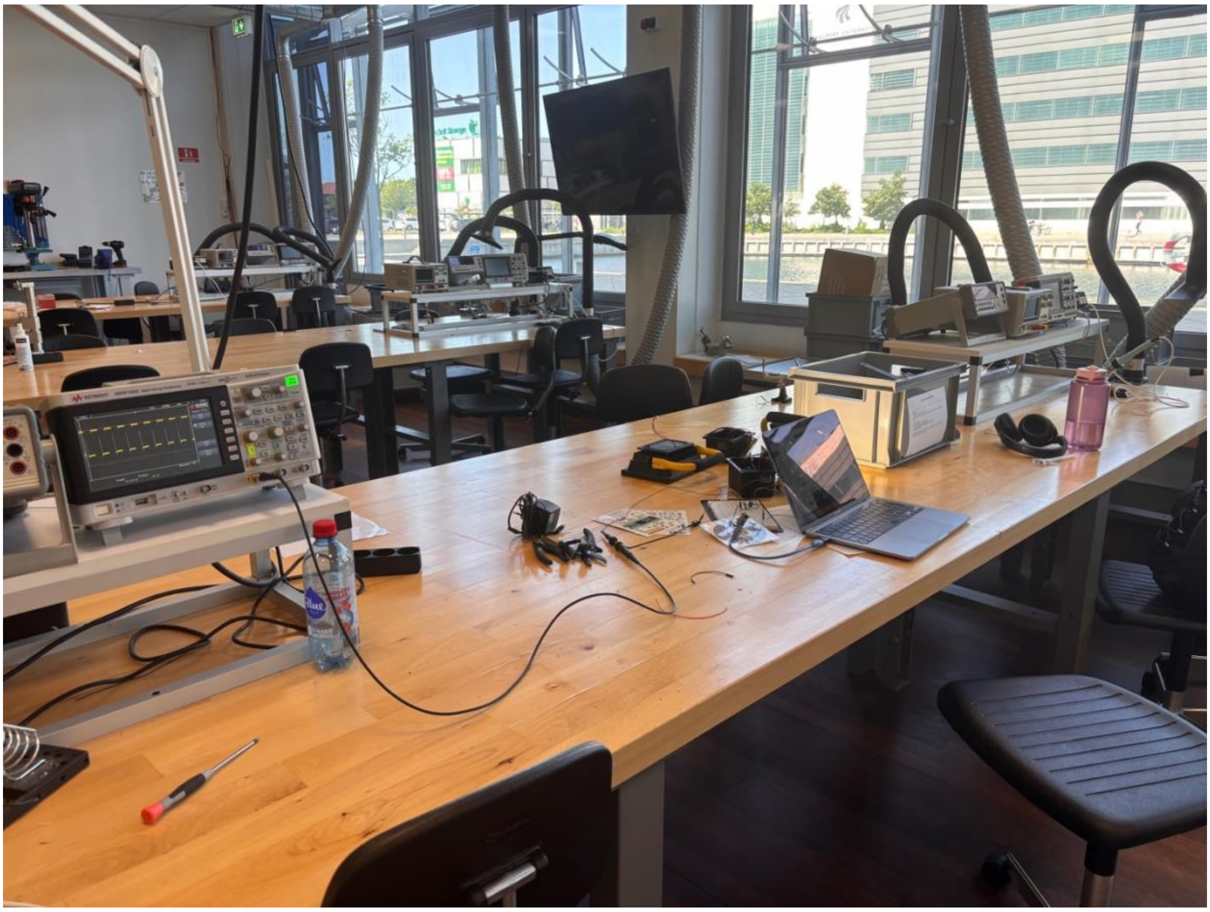
Appendix 1- Literature Review Diagram

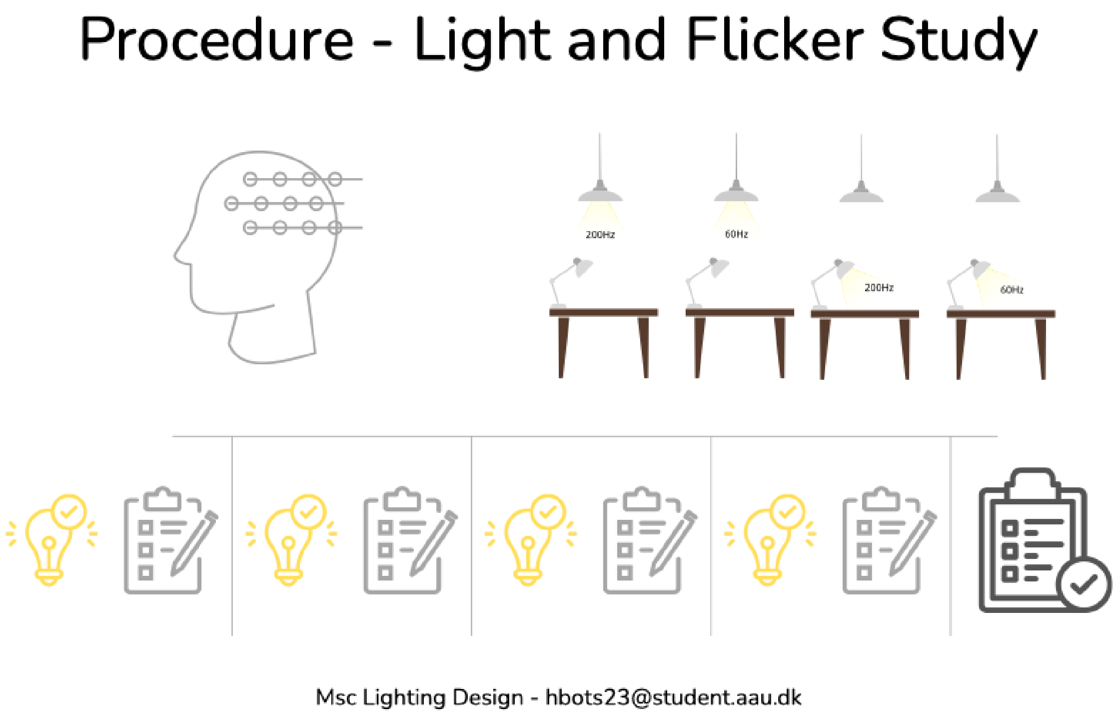


Appendix 2- Creation of the luminaire - breadboard

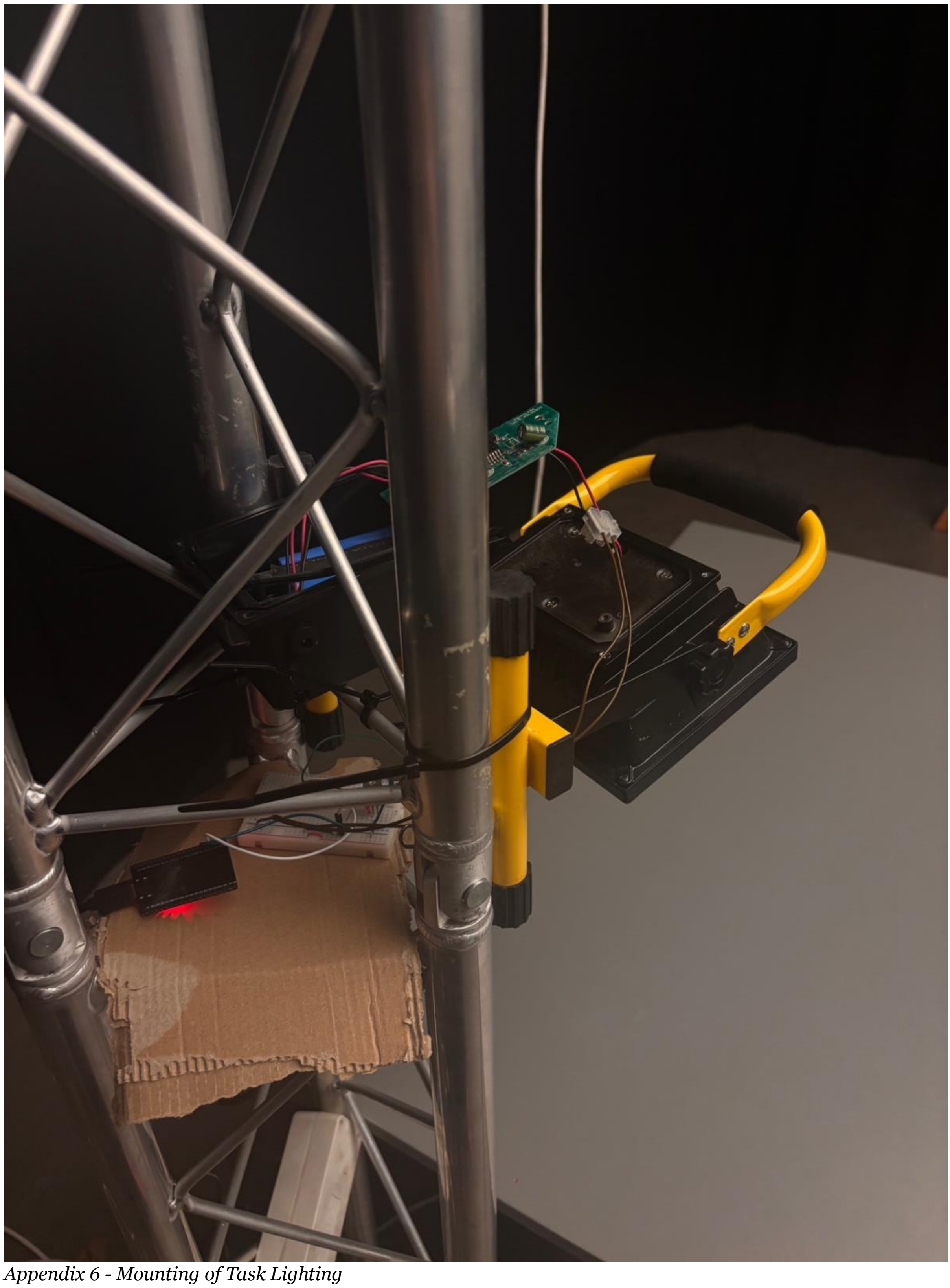


Appendix 3 - Creation of the luminaire - full circuit measuring PWM


Appendix 4 - Creation of the luminaire - PWM testing



Appendix 5 - Visual Explenation of Experiment Procedure

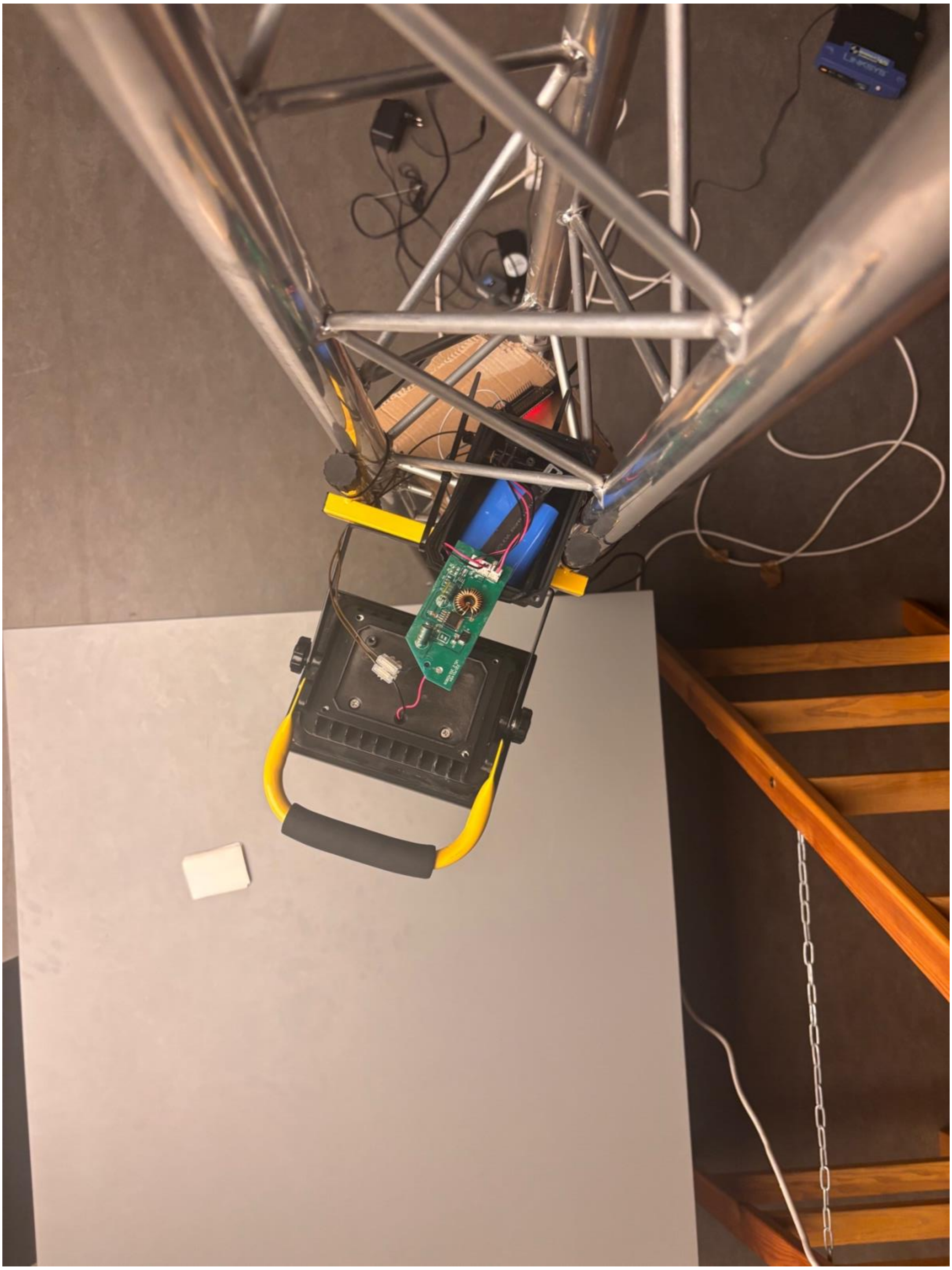


Appendix 6 - Mounting of Task Lighting

Appendix 7 - Mounting General light below view

Appendix 8 - Mounting General Light Above view

Appendix 9 - Above view Task Light



Appendix 10 - Arduino Code

Thesis Experiment Arduino Code

H.J. Bots

```
#include
#include

const char* ssid = "linksys";
const char* password = "";

const int ledPin = 22;
WebServer server(80);

enum LedState {
  OFF,
  FLICKER_FAST,
  FLICKER_SLOW
};

LedState currentState = OFF;

const char* htmlPage = R"rawliteral(
```

ESP32 LED Flicker Control

Click a button to change the LED flicker pattern.

Flicker 1 (200hz)

Flicker 2 (60hz)

Turn Off

```
)rawliteral";

void handleRoot() {
  server.send(200, "text/html", htmlPage);
}

void handleButton1() {
  server.send(200, "text/html", htmlPage);
  currentState = FLICKER_FAST;
}

void handleButton2() {
  server.send(200, "text/html", htmlPage);
  currentState = FLICKER_SLOW;
}

void handleTurnOff() {
  server.send(200, "text/html", htmlPage);
  currentState = OFF;
  digitalWrite(ledPin, LOW);
}

void setup() {
  pinMode(ledPin, OUTPUT);
  Serial.begin(115200);

  Serial.print("Connecting to ");
  Serial.println(ssid);
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
```

```
  Serial.println("\nWiFi connected.");
  Serial.print("IP address: ");
  Serial.println(WiFi.localIP());

  server.on("/", handleRoot);
  server.on("/button1", handleButton1);
  server.on("/button2", handleButton2);
  server.on("/turnOff", handleTurnOff);
  server.begin();
  Serial.println("HTTP server started");
}

void loop() {
  server.handleClient();

  switch (currentState) {
    case FLICKER_FAST:
      digitalWrite(ledPin, HIGH);
      delay(1000 / 350);
      digitalWrite(ledPin, LOW);
      delay(1000 / 350);
      break;

    case FLICKER_SLOW:
      digitalWrite(ledPin, HIGH);
      delay(1000 / 120);
      digitalWrite(ledPin, LOW);
      delay(1000 / 120);
      break;

    case OFF:
      // Nothing to do, the LED is already off.
      break;
  }
}
```

Appendix 11 - Participant Information Form

Participant Information

To begin the study, I'll need to collect some basic demographic information. This data is essential for understanding your unique characteristics and helps me accurately analyze and interpret the results of your (EEG) test. But before we start, please specify on which date, and moment you will do the test:

* Verplichte vraag

1. Date of testing *

   Voorbeeld: 7 januari 2019

2. Time of testing *

   Voorbeeld: 8:30

Participant Information

3. Please write your **age** in the space provided: *

4. Please check the box that best describes your **gende**r: *

   Markeer slechts één ovaal.

   - Female
   - Male
   - Non-binary
   - Prefer not to say

5. Please check the box that describes your **handedness**: *

   Markeer slechts één ovaal.

   - Right-handed
   - Left-handed
   - Ambidextrous

6. Do you have any diagnosed **visual impairments** (e.g., color blindness, corrected vision, etc.) that we should be aware of? *

   Markeer slechts één ovaal.

   - Yes
   - No

7. If you answered **"Yes,"** please specify the nature of the impairment(s):

8. *Only fill out if you wrote "Yes"* - **Glasses or Contact Lenses:** If you wear glasses or contact lenses, please provide your prescription if you know it (e.g., -2.5 for nearsightedness or +1.75 for farsightedness).

Thank you!

All of your information will be kept strictly confidential and used solely for the purpose of this research.

Deze content is niet gemaakt of goedgekeurd door Google.

Google Formulieren

Consent and Duty to Inform

* Verplichte vraag

1. This is a request for your consent to process your personal data. The purpose of the processing is to **collect data on your brain's responses to flicker stimuli**, helping us to bridge the gap in our understanding of how perception relates to brain activity. This method allows us to gather valuable insights directly, minimizing the need for extensive questionnaires. *

   You consent to the processing of the following data about you: The personal data we will process includes your **demographic data (age, gender, etc), brain activity measured by EEG, and responses from a short questionnaire.**

   I, Henderika Johanna Bots, am the data controller of your data.

   Your data will be stored securely, and I will solely use the data for the above purpose.

   You always have the right to change your consent. If you wish to change your consent later on, you can email hbots23@student.aau.dk

   On the next page, I will explain how I process your data.

   Vink alle toepasselijke opties aan.

   ☐ I hereby consent to H.J. Bots processing my data in accordance with the above purpose and information.

2. Date of Signing *

   Voorbeeld: 7 januari 2019

3. Your Name *

Ga naar sectie 2 (How I process your data)

How I process your data

The data controller Henderika Johanna Bots hbots23@student.aau.dk will process your data.
The purpose of processing your data is to **scientifically analyze how visual perception and brain activity are affected by the position of a light source and the frequency of the flickering.**

General Personal Data (Article 6(1)(a)) (name, address, email, age, gender, left or right-handedness.)

Sensitive Personal Data (Article 9(2)(a))
(brain activity (EEG data), health data such as visual impairments.)

The data I will process consists of **demographic data** and **physiological data**.
How I store your data
I will store your personal data for as long as necessary for the data processing purpose for which I am obtaining your consent and in accordance with the applicable legislation. I will then erase your personal data.

Your rights
When I process your personal data, you have several rights under the General Data Protection Regulation. For example, you have a right to erasure and a right to data portability.

In certain cases, you have a right of access, a right to rectification, a right to restriction of processing, and a right to object to our processing of the personal data in question.

Be aware that you cannot withdraw your consent with retroactive effect.
Do you want to complain?

If you believe that I do not meet my responsibility or that I do not process your data according to the rules, you may lodge a complaint with the Danish Data Protection Agency at dt@datatilsynet.dk.

However, I encourage you also to contact me, as I want to do my utmost to accommodate your complaint.

Date:

Time:

In which scenario(s) did you **notice a flicker**?

Cross all that apply

A	B	C	D	NONE

In which scenario(s) did you feel the **most visual discomfort or eye strain**?

Cross all that apply

A	B	C	D	NONE

In which scenario(s) did you feel the **most agitated or unpleasant**?

Cross all that apply

A	B	C	D	NONE

In which scenario(s) was it **most difficult to sort the cards**?

Cross all that apply

A	B	C	D	NONE

Appendix 14 - Python Code - Data Sheet Filtering

Python Code - Data Sheet Filtering

```python
# -*- coding: utf-8 -*-
"""
Thesis Data Cleaning Script

This script loads all CSV files from a specified folder, combines them,
and performs a series of common data cleaning operations.
"""

# 1. SETUP: Import necessary libraries
import pandas as pd
import numpy as np
import os
import glob

# 2. DATA LOADING: Combine all CSV files from a folder

# --- USER INPUT: PLEASE MODIFY THIS PATH ---
# Set the path to the folder containing your 15 CSV files.
# Example for Windows: 'C:/Users/YourName/Documents/Thesis/Data'
# Example for Mac/Linux: '/Users/YourName/Documents/Thesis/Data'
path_to_csv_folder = 'path/to/your/csv/files'

# Check if the path is valid
if not os.path.isdir(path_to_csv_folder):
    print(f"Error: The path '{path_to_csv_folder}' does not exist.")
    print("Please update the 'path_to_csv_folder' variable with the correct location.")
else:
    # Use glob to find all files in the folder ending with .csv
    all_files = glob.glob(os.path.join(path_to_csv_folder, "*.csv"))

    if not all_files:
        print(f"Error: No CSV files were found in '{path_to_csv_folder}'.")
        print("Please ensure your CSV files are in the specified folder.")
    else:
        print(f"Found {len(all_files)} CSV files. Combining them now...")

        # Create a list to hold each loaded dataframe
        df_list = []
        for filename in all_files:
            df = pd.read_csv(filename)
            df_list.append(df)

        # Concatenate all dataframes in the list into a single dataframe
        combined_df = pd.concat(df_list, ignore_index=True)

        print("\n--- Initial Data Snapshot ---")
        print("Shape of combined data (rows, columns):", combined_df.shape)
        print("First 5 rows:")
```

```python
print(combined_df.head())
print("\nData types and missing values:")
combined_df.info()


# 3. DATA CLEANING PIPELINE

# --- Step 3.1: Rename columns for consistency ---
# It's good practice to make column names lowercase and replace spaces with underscores.
# --- USER INPUT: PLEASE MODIFY THESE COLUMN NAMES ---
# Replace with your actual column names. Assuming 4 columns as requested.
original_column_names = combined_df.columns.tolist() # Gets the current names
new_column_names = ['participant_id', 'timestamp', 'measurement_value', 'condition']

if len(original_column_names) == len(new_column_names):
    combined_df.columns = new_column_names
    print("\n--- Renamed Columns ---")
    print(f"Columns renamed to: {new_column_names}")
else:
    print("\nWarning: Number of new column names does not match number of columns in data. Skipping renaming.")


# --- Step 3.2: Handle Missing Values ---
# Option A: Drop rows with any missing values (simple and effective if you have lots of data)
cleaned_df = combined_df.dropna()
print(f"\n--- Handling Missing Values ---")
print(f"{len(combined_df) - len(cleaned_df)} rows were dropped due to missing values.")

# Option B (Alternative): Fill missing numerical values with the mean or median.
# Uncomment the lines below to use this instead of dropping.
# for col in ['measurement_value']: # Specify your numerical columns
#     if pd.api.types.is_numeric_dtype(cleaned_df[col]):
#         median_val = cleaned_df[col].median()
#         cleaned_df[col].fillna(median_val, inplace=True)
#         print(f"Filled missing values in '{col}' with median ({median_val}).")


# --- Step 3.3: Correct Data Types ---
# Convert columns to their appropriate types (e.g., numbers, dates, categories).
# --- USER INPUT: ADJUST AS NEEDED ---
print("\n--- Correcting Data Types ---")
# Convert a column to a numeric type, coercing errors to 'NaN' (Not a
```

```
Number)
        cleaned_df['measurement_value'] = pd.to_numeric(cleaned_df['measurement_value'], errors='coerce')

        # Convert a column to datetime objects
        cleaned_df['timestamp'] = pd.to_datetime(cleaned_df['timestamp'], errors='coerce')

        # Convert a column with a limited set of text values to a more efficient 'category' type
        cleaned_df['condition'] = cleaned_df['condition'].astype('category')

        # After coercing, we might have new NaN values, so we drop them again.
        rows_before = len(cleaned_df)
        cleaned_df.dropna(inplace=True)
        print(f"{rows_before - len(cleaned_df)} rows dropped due to data type conversion errors.")
        print("Data types after correction:")
        cleaned_df.info()


        # --- Step 3.4: Remove Duplicate Rows ---
        rows_before_duplicates = len(cleaned_df)
        cleaned_df.drop_duplicates(inplace=True)
        rows_after_duplicates = len(cleaned_df)
        print(f"\n--- Removing Duplicates ---")
        print(f"{rows_before_duplicates - rows_after_duplicates} duplicate rows were removed.")


        # --- Step 3.5: Remove Outliers (using the IQR method) ---
        # This is a common statistical method to remove extreme values.
        # We will only apply this to the 'measurement_value' column.
        print("\n--- Removing Outliers ---")
        Q1 = cleaned_df['measurement_value'].quantile(0.25)
        Q3 = cleaned_df['measurement_value'].quantile(0.75)
        IQR = Q3 - Q1 # Interquartile Range

        # Define the outlier boundaries
        lower_bound = Q1 - 1.5 * IQR
        upper_bound = Q3 + 1.5 * IQR

        rows_before_outliers = len(cleaned_df)
        # Filter the dataframe to keep only the rows that are NOT outliers
        cleaned_df = cleaned_df[
            (cleaned_df['measurement_value'] >= lower_bound) &
            (cleaned_df['measurement_value'] <= upper_bound)
        ]
        rows_after_outliers = len(cleaned_df)
        print(f"{rows_before_outliers - rows_after_outliers} outliers were removed from 'measurement_value'.")
```

```
    # 4. FINAL REVIEW AND SAVE ✅

    print("\n--- Final Cleaned Data Summary ---")
    print("Shape of final data (rows, columns):", cleaned_df.shape)
    print("Statistical description of numerical columns:")
    print(cleaned_df.describe())

    # --- USER INPUT: CHOOSE YOUR FILENAME ---
    output_filename = 'cleaned_thesis_data.csv'
    output_path = os.path.join(path_to_csv_folder, output_filename)

    # Save the final, cleaned dataframe to a new CSV file
    cleaned_df.to_csv(output_path, index=False)

    print(f"\nSUCCESS! ✨ Cleaned data has been saved to:\n{output_pat
h}")
```

Appendix 15 - Python Code - Visualization - Subjective Ratings and EEG Bandpower Distribution Across Scenarios

Python Code - Visualization - Subjective Ratings and EEG Bandpower Distribution Across Scenarios

```python

import pandas as pd
import plotly.graph_objects as go
from plotly.subplots import make_subplots

# Create a copy of the ordered dataframe to avoid modifying the original
df_plot = df_ordered.copy()

# Add a 'Participant' column with IDs from P01 to P16 and exclude P02
df_plot['Participant'] = [f'P{i:02d}' for i in range(1, 17)]
df_plot = df_plot[df_plot['Participant'] != 'P02']


# Reshape the data from a wide to a long format for easier plotting
data_long = []
for col in df_plot.columns:
    if col == 'Participant':
        continue
    parts = col.split('_')
    # Parse scenario and measure from the column names
    if "EEG" in col:
        scenario = parts[2]
        measure = parts[1]
    else:
        scenario = parts[0]
        measure = parts[1]

    # Create a temporary dataframe for each measure and append it
    temp_df = pd.DataFrame({
        'Scenario': scenario,
        'Measure': measure,
        'Value': df_plot[col]
    })
    data_long.append(temp_df)

# Concatenate all temporary dataframes into a single long-format dataframe
df_long = pd.concat(data_long, ignore_index=True)

# Define the mapping for scenario names and apply it
scenario_map = {
    'A': 'A: General, 200Hz',
    'B': 'B: Task, 60Hz',
    'C': 'C: Task, 200Hz',
    'D': 'D: General, 60Hz'
}
df_long['Scenario'] = df_long['Scenario'].map(scenario_map)


```

```python
# Create a figure with a secondary y-axis to handle different scales
fig = make_subplots(specs=[[{"secondary_y": True}]])

# Define the measures and their corresponding colors
subjective_measures = ['Arousal', 'Valence', 'Difficulty']
eeg_measures = ['Alpha', 'Beta', 'Gamma']
colors = ['#EC4899', '#A855F7', '#6366F1', '#3B82F6', '#06B6D4', '#14B8A6']
color_map = {measure: color for measure, color in zip(subjective_measures + eeg_measures, colors)}

# Add boxplots for subjective measures to the primary y-axis
for measure in subjective_measures:
    df_measure = df_long[df_long['Measure'] == measure]
    fig.add_trace(
        go.Box(
            x=df_measure['Scenario'],
            y=df_measure['Value'],
            name=measure,
            marker_color=color_map[measure]
        ),
        secondary_y=False,
    )

# Add boxplots for EEG measures to the secondary y-axis
for measure in eeg_measures:
    df_measure = df_long[df_long['Measure'] == measure]
    fig.add_trace(
        go.Box(
            x=df_measure['Scenario'],
            y=df_measure['Value'],
            name=measure,
            marker_color=color_map[measure]
        ),
        secondary_y=True,
    )

# Update the layout for clarity and readability
fig.update_layout(
    title_text='Subjective Ratings and EEG Bandpower Distribution Across Scenarios (P02 Excluded)',
    boxmode='group',  # Group boxplots by scenario
    xaxis_title='Scenario',
    width=1000,
    height=600,
    xaxis=dict(
        categoryorder='array',
        categoryarray=[
            'A: General, 200Hz',
            'B: Task, 60Hz',
            'C: Task, 200Hz',
            'D: General, 60Hz'
        ]
```

```
    ),
    yaxis=dict(
        title='Subjective Rating (Likert Scale)',
    ),
    yaxis2=dict(
        title='EEG Bandpower (µV²)',
        overlaying='y',
        side='right'
    ),
    legend=dict(
        orientation="h",
        yanchor="bottom",
        y=1.02,
        xanchor="right",
        x=1
    )
)

fig.show()
```

Python Code - Visualization - Effect of Luminaire Position on Perceived Task Difficulty and Average Gamma Power

```
import pandas as pd
import numpy as np
import plotly.graph_objects as go
from plotly.subplots import make_subplots
from scipy import stats

# --- 1. Data Preparation with new subjective data ---
# New means and SDs for Perceived Task Difficulty
difficulty_stats = {
    'A': {'mean': 1.67, 'sd': 0.98},
    'B': {'mean': 3.67, 'sd': 1.95},
    'C': {'mean': 1.67, 'sd': 1.11},
    'D': {'mean': 2.33, 'sd': 1.54}
}
n_samples = 15
np.random.seed(42)

# Create a copy of the filtered dataframe
df_plot_filtered = df_ordered[df_ordered['Participant'] != 'P02'].copy()

# Generate new difficulty data and create a new dataframe for plotting
participants = df_plot_filtered['Participant']
new_data = {'Participant': participants}

# Add new difficulty data
for scenario_letter, stats_vals in difficulty_stats.items():
    new_data[f'{scenario_letter}_Difficulty'] = np.random.normal(loc=stats_vals['mean'], scale=stats_vals['sd'], size=n_samples)

# Add existing gamma data
for scenario_letter in ['A', 'B', 'C', 'D']:
    new_data[f'EEG_Gamma_{scenario_letter}'] = df_plot_filtered[f'EEG_Gamma_{scenario_letter}'].values

df_plot_new = pd.DataFrame(new_data)


# --- 2. Data Reshaping ---
# Melt the new dataframe for Perceived Task Difficulty
difficulty_df = df_plot_new.melt(
    id_vars=['Participant'],
    value_vars=['A_Difficulty', 'B_Difficulty', 'C_Difficulty', 'D_Difficulty'],
    var_name='Scenario_Code',
    value_name='Perceived Task Difficulty'
)
difficulty_df['Scenario_Letter'] = difficulty_df['Scenario_Code'].str.split
```

```
('_').str[0]

# Melt the dataframe for Average Gamma Power
gamma_df = df_plot_new.melt(
    id_vars=['Participant'],
    value_vars=['EEG_Gamma_A', 'EEG_Gamma_B', 'EEG_Gamma_C', 'EEG_Gamma_D'],
    var_name='Scenario_Code',
    value_name='Average Gamma Power'
)
gamma_df['Scenario_Letter'] = gamma_df['Scenario_Code'].str.split('_').str[2]

# Combine into a single long-format dataframe
plot_df = pd.merge(difficulty_df, gamma_df, on=['Participant', 'Scenario_Letter'])

# Define the mapping for scenario names and apply it
scenario_map = {
    'A': 'A: General, 200Hz',
    'B': 'B: Task, 60Hz',
    'C': 'C: Task, 200Hz',
    'D': 'D: General, 60Hz'
}
plot_df['Scenario'] = plot_df['Scenario_Letter'].map(scenario_map)


# --- 3. P-value Calculation & Plotting for Luminaire Position ---
# Ensure the order of scenarios for luminaire position comparison
scenario_order = ['A: General, 200Hz', 'C: Task, 200Hz', 'D: General, 60Hz', 'B: Task, 60Hz']
plot_df['Scenario'] = pd.Categorical(plot_df['Scenario'], categories=scenario_order, ordered=True)
plot_df = plot_df.sort_values('Scenario')

# P-values for Task Difficulty (from user)
p_val_ac_diff = 1.00
p_val_db_diff = 0.0406

# P-values for Gamma Power (calculated from data)
a_gamma = plot_df[plot_df['Scenario'] == 'A: General, 200Hz']['Average Gamma Power']
c_gamma = plot_df[plot_df['Scenario'] == 'C: Task, 200Hz']['Average Gamma Power']
p_val_ac_gamma = stats.ttest_ind(a_gamma, c_gamma).pvalue

d_gamma = plot_df[plot_df['Scenario'] == 'D: General, 60Hz']['Average Gamma Power']
b_gamma = plot_df[plot_df['Scenario'] == 'B: Task, 60Hz']['Average Gamma Power']
p_val_db_gamma = stats.ttest_ind(d_gamma, b_gamma).pvalue

```

```python
# Create the plot
fig = make_subplots(specs=[[{"secondary_y": True}]])
fig.add_trace(go.Box(x=plot_df['Scenario'], y=plot_df['Perceived Task Difficulty'], name='Perceived Task Difficulty', marker_color='#6366F1', boxmean=True), secondary_y=False)
fig.add_trace(go.Box(x=plot_df['Scenario'], y=plot_df['Average Gamma Power'], name='Average Gamma Power', marker_color='#F97316', boxmean=True), secondary_y=True)

# Add annotations
y_max_diff = plot_df['Perceived Task Difficulty'].max()
y_max_gamma = plot_df['Average Gamma Power'].max()

fig.add_shape(type="line", x0=0, y0=y_max_diff + 1, x1=1, y1=y_max_diff + 1, line=dict(color="black", width=1), secondary_y=False)
fig.add_annotation(x=0.5, y=y_max_diff + 1.5, text=f"TD: p={p_val_ac_diff:.4f}", showarrow=False, secondary_y=False)
fig.add_annotation(x=0.5, y=y_max_gamma + 1.5, text=f"GP: p={p_val_ac_gamma:.4f}", showarrow=False, secondary_y=True)

fig.add_shape(type="line", x0=2, y0=y_max_diff + 1, x1=3, y1=y_max_diff + 1, line=dict(color="black", width=1), secondary_y=False)
fig.add_annotation(x=2.5, y=y_max_diff + 1.5, text=f"TD: p={p_val_db_diff:.4f}", showarrow=False, secondary_y=False)
fig.add_annotation(x=2.5, y=y_max_gamma + 1.5, text=f"GP: p={p_val_db_gamma:.4f}", showarrow=False, secondary_y=True)

# Final Touches
fig.update_layout(
    title_text='Effect of Luminaire Position on Perceived Task Difficulty and Average Gamma Power (P02 Excluded)',
    width=800, height=600, boxmode='group',
    xaxis=dict(title='Lighting Scenarios'),
    yaxis=dict(title='Perceived Task Difficulty (1-7 Likert Scale)', range=[0, y_max_diff + 3]),
    yaxis2=dict(title='Average Gamma Power (µV²)', overlaying='y', side='right', range=[0, y_max_gamma + 3]),
    legend=dict(orientation="h", yanchor="bottom", y=1.02, xanchor="right", x=1)
)
fig.show()
```

Appendix 17 - Python Code - Visualization - Effect of Flicker Frequency on Perceived Task Difficulty and Average Gamma Power

Python Code - Visualization - Effect of Flicker Frequency on Perceived Task Difficulty and Average Gamma Power

```python

import pandas as pd
import numpy as np
import plotly.graph_objects as go
from plotly.subplots import make_subplots
from scipy import stats

# --- 1. Data Preparation with new subjective data ---
# New means and SDs for Perceived Task Difficulty
difficulty_stats = {
    'A': {'mean': 1.67, 'sd': 0.98},
    'B': {'mean': 3.67, 'sd': 1.95},
    'C': {'mean': 1.67, 'sd': 1.11},
    'D': {'mean': 2.33, 'sd': 1.54}
}
n_samples = 15
np.random.seed(42)

# Create a copy of the filtered dataframe
df_plot_filtered = df_ordered[df_ordered['Participant'] != 'P02'].copy()

# Generate new difficulty data and create a new dataframe for plotting
participants = df_plot_filtered['Participant']
new_data = {'Participant': participants}

# Add new difficulty data
for scenario_letter, stats_vals in difficulty_stats.items():
    new_data[f'{scenario_letter}_Difficulty'] = np.random.normal(loc=stats_vals['mean'], scale=stats_vals['sd'], size=n_samples)

# Add existing gamma data
for scenario_letter in ['A', 'B', 'C', 'D']:
    new_data[f'EEG_Gamma_{scenario_letter}'] = df_plot_filtered[f'EEG_Gamma_{scenario_letter}'].values

df_plot_new = pd.DataFrame(new_data)


# --- 2. Data Reshaping ---
# Melt the new dataframe for Perceived Task Difficulty
difficulty_df = df_plot_new.melt(
    id_vars=['Participant'],
    value_vars=['A_Difficulty', 'B_Difficulty', 'C_Difficulty', 'D_Difficulty'],
    var_name='Scenario_Code',
    value_name='Perceived Task Difficulty'
)
difficulty_df['Scenario_Letter'] = difficulty_df['Scenario_Code'].str.split
```

```
('_').str[0]

# Melt the dataframe for Average Gamma Power
gamma_df = df_plot_new.melt(
    id_vars=['Participant'],
    value_vars=['EEG_Gamma_A', 'EEG_Gamma_B', 'EEG_Gamma_C', 'EEG_Gamma_D'],
    var_name='Scenario_Code',
    value_name='Average Gamma Power'
)
gamma_df['Scenario_Letter'] = gamma_df['Scenario_Code'].str.split('_').str[2]

# Combine into a single long-format dataframe
plot_df = pd.merge(difficulty_df, gamma_df, on=['Participant', 'Scenario_Letter'])

# Define the mapping for scenario names and apply it
scenario_map = {
    'A': 'A: General, 200Hz',
    'B': 'B: Task, 60Hz',
    'C': 'C: Task, 200Hz',
    'D': 'D: General, 60Hz'
}
plot_df['Scenario'] = plot_df['Scenario_Letter'].map(scenario_map)


# --- 3. P-value Calculation & Plotting for Flicker Frequency ---
# Ensure the order of scenarios for flicker frequency comparison
scenario_order = ['A: General, 200Hz', 'D: General, 60Hz', 'C: Task, 200Hz', 'B: Task, 60Hz']
plot_df['Scenario'] = pd.Categorical(plot_df['Scenario'], categories=scenario_order, ordered=True)
plot_df = plot_df.sort_values('Scenario')

# P-values for Task Difficulty (from user)
p_val_ad_diff = 0.096
p_val_cb_diff = 0.0031

# P-values for Gamma Power (calculated from data)
a_gamma = plot_df[plot_df['Scenario'] == 'A: General, 200Hz']['Average Gamma Power']
d_gamma = plot_df[plot_df['Scenario'] == 'D: General, 60Hz']['Average Gamma Power']
p_val_ad_gamma = stats.ttest_ind(a_gamma, d_gamma).pvalue

c_gamma = plot_df[plot_df['Scenario'] == 'C: Task, 200Hz']['Average Gamma Power']
b_gamma = plot_df[plot_df['Scenario'] == 'B: Task, 60Hz']['Average Gamma Power']
p_val_cb_gamma = stats.ttest_ind(c_gamma, b_gamma).pvalue

```

```
# Create the plot
fig = make_subplots(specs=[[{"secondary_y": True}]])
fig.add_trace(go.Box(x=plot_df['Scenario'], y=plot_df['Perceived Task Difficulty'], name='Perceived Task Difficulty', marker_color='#6366F1', boxmean=True), secondary_y=False)
fig.add_trace(go.Box(x=plot_df['Scenario'], y=plot_df['Average Gamma Power'], name='Average Gamma Power', marker_color='#F97316', boxmean=True), secondary_y=True)

# Add annotations
y_max_diff = plot_df['Perceived Task Difficulty'].max()
y_max_gamma = plot_df['Average Gamma Power'].max()

fig.add_shape(type="line", x0=0, y0=y_max_diff + 1, x1=1, y1=y_max_diff + 1, line=dict(color="black", width=1), secondary_y=False)
fig.add_annotation(x=0.5, y=y_max_diff + 1.5, text=f"TD: p={p_val_ad_diff:.4f}", showarrow=False, secondary_y=False)
fig.add_annotation(x=0.5, y=y_max_gamma + 1.5, text=f"GP: p={p_val_ad_gamma:.4f}", showarrow=False, secondary_y=True)

fig.add_shape(type="line", x0=2, y0=y_max_diff + 1, x1=3, y1=y_max_diff + 1, line=dict(color="black", width=1), secondary_y=False)
fig.add_annotation(x=2.5, y=y_max_diff + 1.5, text=f"TD: p={p_val_cb_diff:.4f}", showarrow=False, secondary_y=False)
fig.add_annotation(x=2.5, y=y_max_gamma + 1.5, text=f"GP: p={p_val_cb_gamma:.4f}", showarrow=False, secondary_y=True)

# Final Touches
fig.update_layout(
    title_text='Effect of Flicker Frequency on Perceived Task Difficulty and Average Gamma Power (P02 Excluded)',
    width=800, height=600, boxmode='group',
    xaxis=dict(title='Lighting Scenarios'),
    yaxis=dict(title='Perceived Task Difficulty (1-7 Likert Scale)', range=[0, y_max_diff + 3]),
    yaxis2=dict(title='Average Gamma Power (µV²)', overlaying='y', side='right', range=[0, y_max_gamma + 3]),
    legend=dict(orientation="h", yanchor="bottom", y=1.02, xanchor="right", x=1)
)
fig.show()

```