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Investigating the correlation between melanopic response and emotions using EEG analysis

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Abstract:

This work aims to investigate the correlation of the impact of lighting on circadian rhythm, and the impact of lighting in emotions (arousal and valence) in real and virtual environments by using an electroencephalogram (EEG) test, which is a reliable and cost-effective methodology used to measure brain activity.

Using EEG, the emotions of the user can be recognized by analyzing the different brain signal waves generated accordingly. A sample size of 15 participants was recruited for the study in an office space, where participants were exposed to daylight and electrical lighting, and were asked to perform practical activities. To measure the effects of lighting, brain activity was continuously measured with an EEG helmet, and the melanopic equivalent daylight illuminance (EDI) was measured at the eye level, with a spectrometer in the real environment and with ALFA software in the virtual reality. Additionally, a questionnaire using the Self-Assessment Manikin (SAM) approach was provided to participants to assess the subjective levels of valence and arousal, in order to cross check and validate the EEG data.

The study design aimed to find the correlations between the melanopic EDI and the increase/decrease in alpha, beta, and gamma brain waves, which are connected to high/low valence and arousal (also cross checked with the questionnaires). Correlations between the melanopic EDI, brain activity, and emotional states, could provide valuable insights for designing environments that promote optimal circadian health and emotional well-being. This work also compares the results between real and virtual environments to validate how VR could be a valuable tool not only to display an upcoming space and light setting but also bring the experience even further closer to reality by mimicking the emotional response.

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0. Motivation

The following Master's thesis presents the combination and the outcome of the original collaboration of the two authors, attending the Master of Science in Lighting Design.
The study and investigation being presented are the results of different and common interests, intentions and commitments aroused in the course of this two-year program.

On one hand the sincere relevance of the innovation study being carried out during the third semester, where circadian lighting in office space, has been investigated. The examination aimed to find a proper balance of the circadian rhythm for the inhabitants of office spaces, considering both daylight and electrical lighting and how they impact the metric of mEDI[1].
In this regard, a pilot test has been conceived, spread over a ten-day period, with different measurements with the spectrometer each day, to analyze the dynamics of daylight, for eight positions within the space and two directions of view.
In the meantime, a similar procedure has been set up using a lighting simulation software that sought to validate the detections and possibly, give back an accurate and reliable grade of fidelity.
The findings from the study suggested a first attempt to describe the path along a time period for both daylight and electrical lighting, being useful for proper activation of the circadian rhythm; moreover, it resulted in good suggestions with provision and balance between the two sources. Finally, lighting software was shown to be a useful and accurate tool for lighting practitioners to foresee not only the visual but also the non-visual effect of light.

On the contrary, digital production and the utilization of digital backgrounds in film and television are rapidly evolving fields, with limited accessible information for the public. Consequently, shooting scenes of this nature often involves an experimental approach, but as technology continues to advance and digital production gains popularity, more resources and information are becoming increasingly accessible to individuals interested in pursuing this aspect of film and television.
Through observations and experiments, valuable insights into the characteristics of light have been gained. It has been discovered that illuminating a building is not significantly different from lighting a face or creating a specific atmosphere Lighting plays a crucial role in any movie, particularly within the realm of digital production, as it has the power to set the mood and atmosphere of a scene, influencing the audience's emotional response. Consideration of lighting techniques and experimentation with different approaches have been found essential in achieving the desired look and feel for each scene. Furthermore, the utilization of camera equipment and video processing tools like DaVinci has provided a deeper understanding of lighting skills, improving the ability to create captivating videos and effectively present future projects. The focus of the semester's project centred on creating a movie about the Sisyphus trials, conveying the story through light and symbolism. Digital production served as a tool, employing various lighting techniques based on the theory of complementary colours to bring the narrative to life in a visually captivating manner.

1. Introduction

1.1 Background

Light is a term that refers to what we perceive with our eyes, as a quantity of the visible spectrum, in the range of 380 nm to 780 nm, deriving from the sun which is the primary source of light[1]. Within this range, daylighting is undoubtedly the most beneficial source for humans and certainly, plays an important role with all its qualities and as a consequence has many implications[2].

Furthermore, from the second half of the 19th century, a long-lasting, alternative and efficient source of light, known as the incandescent bulb, made its appearance and illuminated both indoor and outdoor spaces. Ever since then, technology in the lighting design field has seen a huge spread of new and efficient alternatives that now differ for the spectrum they emit, the lumen output, the correlated colour temperature and many other variables.

This made it possible for humans and their well-being to be influenced either in built environments, such as living and work spaces with all their related daily activities and tasks.

On the wave of recent technological progress, VR, which is an abbreviation for virtual reality, refers to a process of mental transcendence into a three-dimensional virtual environment that concretely does not exist in fact. It is essentially a computing technique that immersively manipulates the user's senses to make him/her feel present in the simulated virtual space. Even though this tool was first developed in the mid-1960s[3], and subsequently tested and frequently used in space, flight, and military training and research, after almost five decades it finally reached the consecration of a valid tool to replicate immersive imaginary spaces. To make it possible to dive into virtual realism, nowadays head-mounted displays (HMDs) are needed in order to close and isolate the field of view of a person and so display such a virtual environment. As a greater innovation, its potential is considered endless, with incredible effects and applications, accelerated by the fast pacing developments, and its growth is expected to keep rising. On top of that, virtual reality is a great tool that recently has shown significant importance for evaluating as a method for the design process; more and more practitioners are adopting this method for immersively visualizing indoor environments in buildings. Architects and designers are now able to collaborate virtually with more convenience, control and time-saving conditions, which has indeed been proved and emphasized by researchers for their ability to be efficient and accurate means for design[4].

With the uprising of Covid-19, all world inhabitants were forced to live in their houses, standing the local regulations that also included the importance of social distancing; as a consequence, all the job fields began with the remote working mode and by analyzing this trend, various industries pushed to explore face-to-face alternatives, making it possible for better communication and collaborations. As COVID-19 regulations were enacted in 2020 and in 2021, the virtual reality industry witnessed a rapid boom[5].

In recent years the concept of Metaverse has been gaining a load of interest and just began to emerge in public opinion. According to Ball, this might be best understood as "a quasi-successor state to the mobile internet"[6]. Fundamentally, it is convenient to keep in mind that it will not replace the internet, but rather will build upon and iteratively transform it.

Despite its huge contradictions and good premises, Metaverse is expected to define new ways of paradigms for the way we work, for instance, new hybrid work environments but also, no ways to socialize and entertain[7]. One of the most crucial outcomes since the outbreak of COVID-19 is the demand for personalized spaces, due to the change in the utilization of indoor spaces.
Although, Metaverse is a 3D online virtual world that by means of technologies such as Augmented Reality (AR) and Virtual Reality (VR) is meant to bring and uncover the potential to hold and immerse in this new dimension, Metaverse and its implications for individuals, businesses, and society offer many opportunities and challenges that need to be examined[7].

However, when it comes to Lighting, immersive virtual environments could lead to opposing positions in the scientific community. For instance, in the 1990s, it was suggested, due to the rising interest in the field, the idea of using different types of VR devices, aiming for the prevention and treatment of both mental and physiological health problems[8]. In their review paper, White P.M. et al., reported the benefits of replacing the "in-vivo" experience with forms of "virtual" contact, to cope with some benefits of the natural environment in the virtual one in health and care settings. Relevant applications have been recognized to deal with such strategies, for instance, to deal with the optimization of exposure to sunlight, which is of particular relevance because it is crucial for the production of vitamin D in humans. Another important aspect is related to the fact that being exposed to daylight stimulates alertness, controls the circadian rhythm and many other physiological functions contributing to health and well-being. Unfortunately, VR must not be considered as a replacement for such exposure, due to differences in the spectrum of the emitted light from a VR headset, which is less enriched in wavelengths than the one emitted by daylight and moreover by its relatively small luminance range.
Although this innovative health treatment demonstrated to be efficient in regards to helping combat mood disorders among individuals who experience a lack of direct sunlight[9], future researchers aim to seek and provide new ways for additional health benefits.

Using this powerful tool for the above-mentioned purposes, of balancing the light exposure of an individual has a counter effect that can not properly track how the individual's circadian rhythm using VR, will be affected.
The experience of daylight, or whether electrical lighting, has been investigated in conjunction with methods using VR, but only for a subjective assessment of daylit spaces[10], and to quantify the differences between real environments and virtual ones, on the impact of individuals' levels of mental stress[11]. Furthermore, Heydarian A. et al., collected lighting-related behaviour from a large sample of participants, using immersive virtual environments to gain quantitative measures, for instance, the preferred lux level followed by an evaluation of the preferred lighting-related energy consumption, showing at the end, that participants preferred to have maximum simulated daylighting compared to electric lighting[12].

Therefore, it appears more necessary than ever to adopt an additional method to evaluate how strictly an individual experiences light and perhaps have a deep understanding of how it reacts, in regard to both visual and non-visual effects.
Adopting a Neuroscience approach seems a doable way for seeking how our brain is being affected by different lighting conditions. The use of EEG, which stands for "electroencephalography", as a complementary method, gives back valuable information and

records of the brain activity resulting in electrical activity expressed in waves. What is more, EEG is an effective tool that could track instant emotions and this is possible due to its better temporal resolutions[13]. Early experiments on the impact of lighting on human EEG results showed differing outcomes, for instance, Park et al. studied the effects of different colour temperatures and luminance levels on work efficiency and working memory[14]; Dedovic et al. investigated the effects of perceiving and processing psychosocial stress on the human brain using functional imaging[15].
When it comes to explaining the extrinsic correlations of the circadian cycle and brain activity, it must be noted that light has also acute alerting effects as exposure to it, improves neurobehavioral performance, reduces attentional lapses, and activates the waking electroencephalogram. The waking EEG, as stimulated by light, is typically characterized by a decrease in power density in the *delta* and *theta* frequencies[16].

Subjective assessments and physiological data are so gathered in order to give immediate physiological reactions to given situations. However, this method should not be enclosed only for getting instant physiological responses about a certain environment; it needs to be applied on a real and virtual basis, to see if individuals expect to experience some differences, under certain different lighting conditions, in certain values that are connected to the brain activity. Without any doubt, it is now clear that VR provides amazing perspectives that will allow people to change their emotional state. Research has shown the restoration of VR. Nevertheless, connecting the non-visual effect on humans, especially in indoor environments, to be highlighted by the brain activity with an EEG headset, is still not a practice for evaluating the various luminous environments and the awake period. Basic research is still needed regarding the non-visual effects of VR lighting environments, thus, the following master thesis attempts to offer basic research regarding the non-visual effects of VR.

All things considered, the present master thesis seeks to explore to which extent is it possible to correlate how the circadian cycle, induced by light conditions in both a real environment and a virtual one, could affect and trigger the different emotional states of the brain process. The following purpose will be possibly achieved by combining quantitative methods, measuring the melanopic equivalent daylight illuminance (mEDI), the electroencephalography of settled participants, and on the other hand with subjective assessments such as questionnaires and self-assessment evaluation. This thesis will examine how the incident light individuals are exposed to, and the effect on their circadian rhythm as monitored by their EEG, in two different scenarios by reviewing and synthesizing the current state of the knowledge as well as uncovering other processes to deploy the whole argumentation, as described in the next paragraph.

1.2 Scope of the Research

The subject of evaluating the non-visual effects of light in an immersive virtual environment is a complex and not explored topic to discuss, because of all its limitations. This thesis will focus on setting the two defined environmental settings (real and virtual), for a defined space and their evaluation of how each light condition affects the individuals' mental activity by measuring the amount of light our eyes get. Although we can not directly measure, and thus quantify the weight on the circadian rhythm and the impact of the virtual simulation, for both the lighting conditions, the EEG, as well as the subjective assessments, will try to align and get closer to offer a reliable explanation.
Furthermore, objective detections will be carried out to evaluate where the major records occur and subjective assessments will be conducted to value the preferred environment by tracking the level of presence and other indicators to map the emotional state.
The whole procedure for the preliminary test as well as the final experiments will be run in different locations at Aalborg University Copenhagen.

1.3 Motivation and Vision

Since the beginning it was clear that the goal of the present master thesis must point out the complexity of studying the physiological response, with a neuroscience approach using electroencephalography, to highlight the human reaction under different lighting conditions, in both a real environment and a virtual environment.
Furthermore, in regards to the given complexity of the relationship between the non-visual effect of lighting, and thus its impacts on the neuro-physiological system, is yet a not comprehensive topic as there are limited studies on whether light impacts electroencephalographic; however, is it the aim of the current study to present a step towards offering a possible explanation in regards either of the amount of light our eyes captures.

The proposition that has been adopted for the purpose of this study, seeks to find out if there are any possible correlations between the circadian metric of mEDI and brain activity, with regard to the different states of emotions derived from the intrinsic waves of the brain activity. Moreover, the intention to connect to the main objective that drives the authors' motivation, is to investigate how different lighting conditions, specifically daylighting and electrical lighting, could have an impact if evaluated in the double context of a Real as opposed to a Virtual environment.

Based on the knowledge gathered to introduce the topic, the following initial vision has been framed to be investigated:

"Imagine if we could explain what our eyes get, for the activation and support of our circadian rhythm, into how an individual, and his/her mental activity, is impacted by light"

1.4 Report Structure

The following Master thesis manuscripts comprises seven sections by starting to deploy how this topic was conceived given the above-mentioned state of the knowledge, following the above backgrounds, the literature review has been structured to seek for a better understanding of the current state of the research, dividing the main interest of the current thesis into different topic areas. The formulation of the research question will come after and the methodology will come next, describing with an abundance of details. The result section of the experiment is going to be presented and consequently, the summing up of those with a different discussion chapter, concluding with a final section and a brief explanation of future works. The aim of the study is redirected towards the facilities of an academic environment. After the summing up of the findings of the literature review, some eventual gaps will be identified thus leading to the formulation of research questions and hypotheses. Following it will be offered a thorough explanation of the adopted methodology by describing every procedure, intention or test being carried out. Each of the sections will explain in particular which tool for measuring has been used, as well as the software that helped to create the VR experience, by declaring the equipment and the whole process. The body of the final experiment will be presented as the next section and the paragraph explaining the results with the related discussion will come in succession. Finally, a conclusion section will explain and sum up the outcomes of the entire investigation by declaring possible limitations of the study and what is more, offering suggestions for future works.

2 Literature Review

This section presents in a brief and concise way, how the literature review was structured, the selection and screening process and finally the findings with the final collection of relevant papers and with the absolute purpose of seeking gaps in the existing state of the knowledge thus finding evidence that could possibly support further explanations.

2.1 Clusters for the Research

As a first step, the search engine Scopus developed by Elsevier was selected from the various databases available, which made it possible to be redirected to other sources; along this, secondary, thorough research has been performed on Leukos to enrich the selection of resources and offered a broad coverage of research. Lastly, the SciTech Premium Collection was the third prominent search engine being used, which offered a wide coverage of literature and are feasible for conducting organized queries, thanks to its various seeking functions that could include terms, or even differing terminology to provide better results.
The papers primarily focused on the domain of six different identified clusters to base the research which has been related to prominent keywords related to lighting design and architectural design collaboration and ImVE.
The resulting search string used for this study was as follows:

- EEG or "electroencephalography"
- EEG and Circadian Rhythm
- Virtual Reality or "virtual environment"
- EEG and VE combined
- Comparison between Real and Virtual environment
- VR and Circadian Rhythm

The terms were searched within the topics and assessed through their titles and abstracts in a first instance; the literature published from 2020 to present 2023 were included in this review. There were few potentially relevant publications obtained from the search that belonged in a range of two years prior to the period of selection.
Once the results were obtained, a careful analysis followed some criteria for the final screening. The context was set to 'indoor', as the main focus for this research aims to study and analyze office or perhaps academic environments, while outdoor studies were not considered. Only studies that were reported to be performed on humans were included, as long the purpose wanted to evaluate the phase of the circadian rhythm in both real and virtual environments.
Following in Figure 1. it is possible to have a glance at the PRISMA diagram, showing the process used in the literature research to assuring good selection criteria for the whole review. Previous literature research conducted by the authors brought together thirty-seven articles and publications from a database focused on "circadian rhythm"-"light" and "mEDI" so that there was a combination whereas, from two identified clusters, the results were scarce.
As far as the eligibility in terms of the document type, only peer-reviewed journal articles were considered for the review, since they provide more rigorous and in-depth knowledge. The language was set for only English articles and resulted in an overall 250 results from all the

databases being accessed. As can be seen in Figure 1., the final number of papers (N = 61) is the result of a selection process consisting of two phases of screening, aiming to narrow down the articles relevant to the specific search and possibly remove duplicates. Secondly, the next stage sought to exclude works not perfectly match the topic of the research, identified by reading the title and the abstract. Finally, the eligibility of the remaining papers was analyzed through a complete reading of the body of the text.

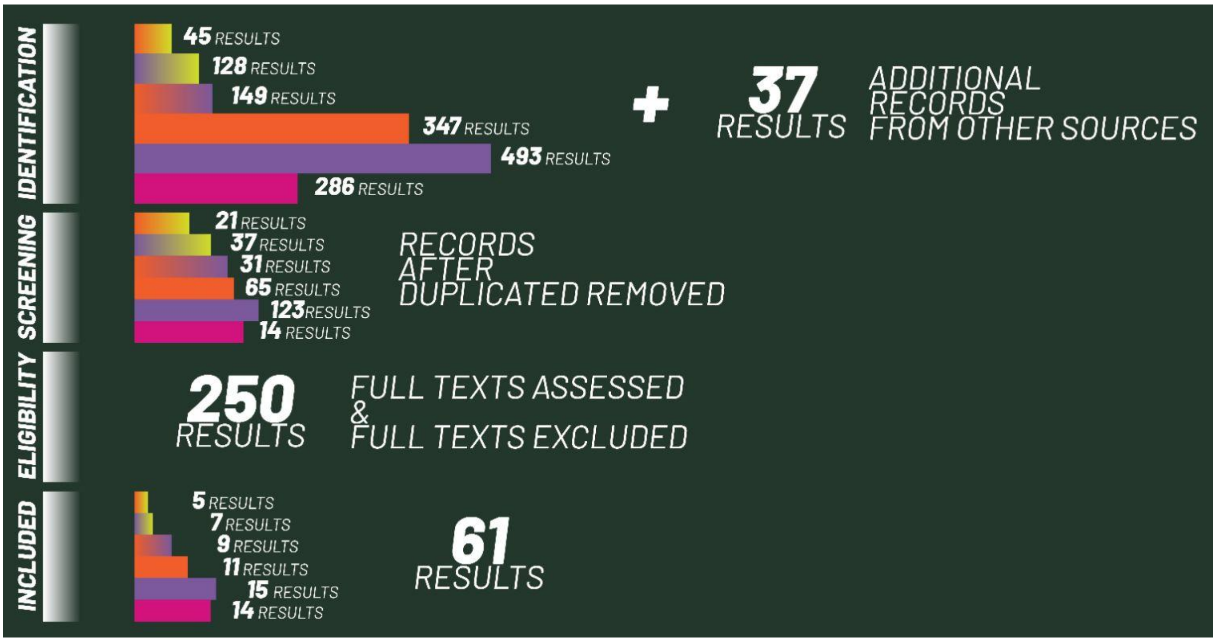

Figure 1.: PRISMA flow diagram with the four steps of the literature process: Identification, Screening, Eligibility and final inclusion for selection.

For instance, papers with a focus on ImVE but for health care and other applications or domains but for the evaluation of lighting conditions were removed. At the end of the process, productive and driving research has defined the basis for seeking existing gaps in the current state of the knowledge.

2.1.1 *Applications of Neuroscience and VR*

One of the most important findings is how more innovative and comprehensive cognitive studies, combining lighting design and neuroscience are emerging in the field to explain and lead to a deeper understanding of the design metrics and EEG to uncover and explain the impact on immersive virtual environments.

In their paper[17], Zhe Kong et al. claim that daylighting qualities influence occupants through both psychological and psychological processes that are still quite not fully understood and this leads to a main concern about still insufficient studies concerning the psychological processes of daylight. This is the point in which the subjective assessment along with physiological data given by electroencephalogram (EEG) could possibly give an explanation of the daylight condition affecting subjective responses. It gives echo Kim S. et al. who applied EEG along with VR to measure the responses of users experiencing changes to architectural elements. Beyond quantitative data, participants were also asked to answer some questionnaires to seek

consistency with the results of the EEG response analysis. As a result, the subjects experiencing VR showed changes in indicator values compared between pre and post-stimulation, by also reporting differences in the relaxation-arousal responses[18].
On the same premises are Chamilothori et al. who claim that VR is a very promising tool to surrogate regard to real environments and the perception of daylit spaces[10].

Hu M., et al explored the role of buildings in shaping human experience by setting up an experimental test using virtual environments and electroencephalogram (EEG) to evaluate the impact of those on occupant cognitive function and mental health[19]. Their findings, based on the observed increased theta/delta activities and greater engagement of visual systems, pointed out that test subjects demonstrated increased visual system engagement and modulated attentional focus and control processing in the virtual environment.

On top of that, they suggest VR in combination with EEG as it could be a great premise to unveil the potential to advance design methods by soliciting occupants' responses prior to the completion of the projects.

2.1.2 Comparing Real vs Virtual Environment

When investigating the relationship between the real environment and the virtual one, due to the recent and promising technologies, one may think that the thin line of realism given by modern immersive scenes offered by render engine and quality VR headset, is almost close to being unnoticed; the perceived realism is a topic has already been investigated for evaluating the success of VR simulations and Xu Jin et al. suggest that, despite studies are needed to map out limitations for VR headsets to simulate real-world settings, acceptable and encouraging baseline are already being reported for perceived realism to fill the gap between these tools[20].
It follows also Kalantari S. et al., as they performed a test replicating a real-world classroom and its identical copy in a virtual space; moreover, they collected physiological data, including EEG and as a result, they observed strong consistency between perceptions in reality and immersive virtual environments[21].

Chamilothori et al. aimed to subjectively assess daylit spaces by creating an experimental method that used a virtual reality (VR) headset, aiming to provide an alternative environment for the conduction and reproduction of daylight[10]. When dealing with daylight, one must take into consideration the rapid and unpredictable changes in its qualities and moreover, the variation of luminous conditions; VR seemed to overcome the difficulties given by little implementations of physically based renderings, by investigating the adequacy of the mentioned method to address five aspects of subjective perception of daylit spaces. The outcomes showed a high level of perceptual accuracy, showing no significant differences
between the real and virtual environments and what is more it was reported a high level of perceived presence in the virtual environment.

On the same premises, to evaluate the perception of daylight in buildings, Hegazy et al. examined an interactive method to investigate daylight brightness perception in IVEs[22].
accurate daylight perception. They introduced Perceptual Light Maps to validate the accuracy across reality and an identical IVE based on real-time rendering in a game engine software and they conclude that a strong consistency between perceptions in reality and IVE has been validated.

2.1.3 *Valence and Arousal*

In order to comprehensively understand the quantitative analysis given by electroencephalography, an important factor that can be used is the concept of the *Valence* and *Arousal* model. It was conceived by Jatupaidboon et al. as a two-dimensional scale, where valence ranges from negative to positive and arousal represents calm to excited[23].
Valence is the pleasantness state generated by a given experience, where for instance unpleasant states are associated with bad feelings or a negative state of mind, while pleasant states are with good feelings[24].

On the other hand, the arousal dimension is the state of activation generated by a given experience, resembling a change in the individual's physical and psychological assets. A deactivated state is associated with a low heart rate and absence of energy; instead, an activated state is associated with a high heartbeat and energy by modulating the quantity of light entering the windows, arousal could be elicited thus promoting circadian rhythms and contributing to people's overall well-being [24].
Tian F. et al studied to which extent virtual reality (VR) can elicit emotions using 2D or 3D headsets, measuring and analysing how these two visual modes impact emotional arousal with the electroencephalography and skin conductance responses (SCR). They found that emotional stimulation was more intense in the 3D environment concerning the 2D[25].
VR was also used by Marìn-Morales J. et al. to examine how it elicits emotions, such as the level of arousal, based on a comparison between the real world and the virtual world. Although they evaluated only employing cardiovascular oscillations of the participants, they observed a 72.92% accuracy for the level of arousal[26].

Regarding concretely mapping human emotions, various measures from time to time have been devised; the most commonly assumed 2D model of emotion classification is arousal and valence proposed by Russell. In this dimension, valence is represented from negative to positive whereas arousal is shown on a scale ranging from not excited to aroused.
Galvão F. et al. availed themselves of the EEG to recognize the state of emotions, and to predict exact values for valence and arousal; they computed features from the alpha, beta and gamma bands, beyond employing datasets thus predicting valence and arousal[27].
Although, according to Galvão et al.[27] there is no a wide consensus on which brain waves to use for emotional analysis when it comes to accuracy, alpha, beta-low and gamma waves have been shown to have the highest.

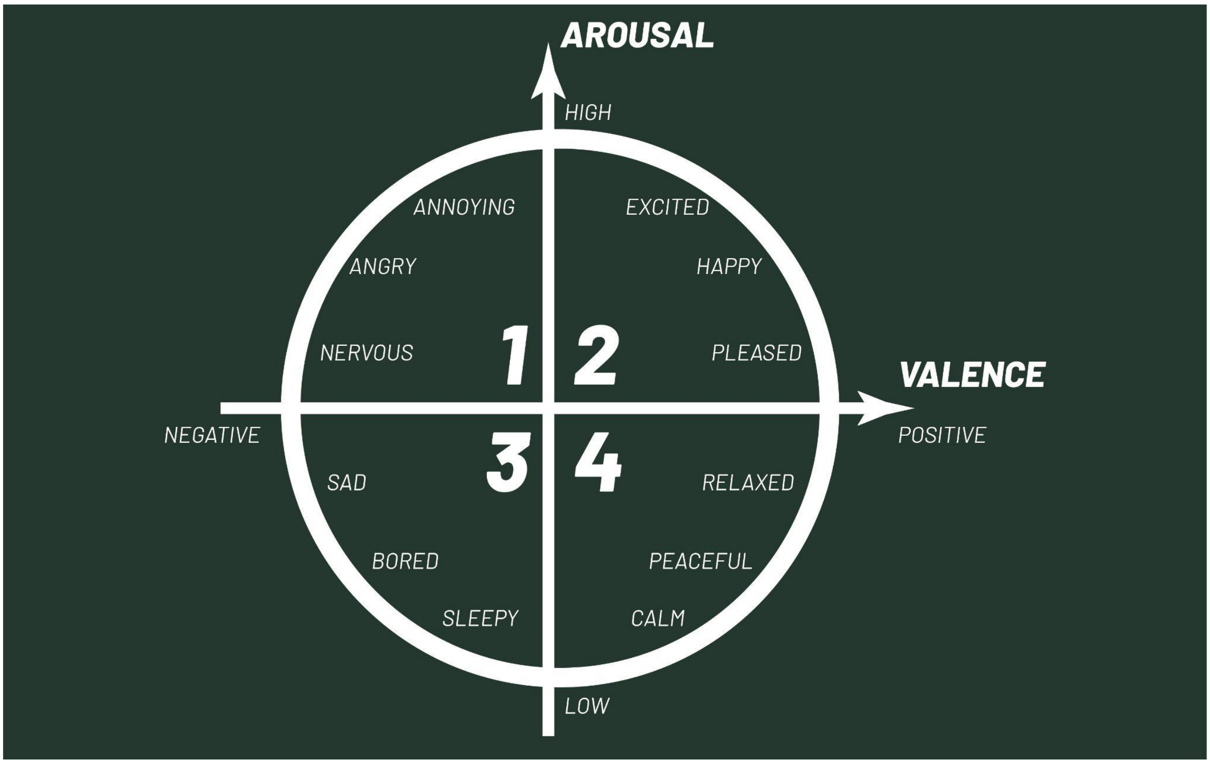

Figure 2.: Russell's Valence Arousal Emotional Model, showing the range of the emotions. (Galvão, et al., 2021)

In this present master thesis research project, we aim to use this dimensional model as a method to compare brain activity with this 2D dimensional model. Moreover, a further objective follows the previous, as a simplification of mapping the valence and arousal, which includes the evaluation of the "High Arousal (HA)" and "Low Arousal (LA)" quadrants. The valence will be similarly mapped into "High Valence (HV)" and "Low Valence (LV)". As a whole, the result of the four quadrants will allow delineation of the state of those emotions.

2.1.4 Circadian Rhythm and VR

As for the existing state of the knowledge between VR and its positive effects on our circadian rhythm, White M. et al, stated that VR use could be an alternative in cases when in vivo contact with nature is not possible[8]. Hence, it highlights the positive and perhaps therapeutic effect of this tool to impact positively on human well-being.
An additional safety reason for it is the ability of VR to promote the inclusion of the older range population or even those who have impairments or inability to perform in the real setting.
The combination of using VR and electroencephalography, as a method during the last decade, has proven to be a reliable way to envision a stronger collaboration within the lighting design field, neuroscience and VR, given the consistent results in studies, such as Hao S. et al. who reported EEG data to bring even more pressure on individuals in the real setting[11], than the VR was supposed to do. Additionally, the non-image-forming (NIF) effects of light exposure have been shown to have physiological and cognitive impacts on humans, having direct and indirect connections to brain areas implicated in the regulation of arousal[28].
Nowadays the non-visual effects of blue light in displays are extensively known and whenever overexposure from the excessive use of digital devices, can disturb the human circadian rhythm. VR headsets, which are worn closer to the human eye, may be considered even more serious and for this reason, Wu T. et al. conducted an evaluation based on a designed system

that makes it possible to measure the impact on our circadian cycle, thus improving the headset by reducing the blue light content[29].

Limited and perhaps scarce findings and relevant articles were found after the above-mentioned literature research about the connected topic of circadian entrainment with VR and EEG. On one hand, the human eye, as it receives light, acts as a type of sensor that transmits signals to the brain through two different pathways and thus is believed to have a connection on the path light-eyes-brain, although research on the non-visual effects of head-mounted devices, such as virtual reality (VR), have yet to be spectroscopically conducted. However, it is significant to consider that these tools are light-emitting devices and most importantly are in close proximity to the eyes. As already mentioned, there is a need to study how these devices in regard circadian entrainment and how affect human non-visual characteristics. Yoon C. et Kim H. proposed an original study[30] in which they addressed the measurements of SPD and how the display light source affects nonvisual characteristics. Furthermore, one of the outlines of the study is that only during long-term exposure, melatonin secretion begins to increase and therefore for a limited time of exposure is not really applicable. What is more, no consistent findings about how to measure directly from VR headsets have ever been found or tested, due to the intrinsic technology and concavity of the lenses.

Our exploration for this thesis aims also to show any possible and reliable correlations between the metric of melanopic equivalent daylight illuminance (mEDI), measured in both of the environments, by means of a spectrometer and a spectral lighting simulation tool.

2.2 Gaps in Knowledge

After the thorough conducted literature review, the research among the six different clusters, suggested some gaps to be resolved to understand entirely the scope of the different topics highlighted with the clusters; these unknown research have been identified and could be listed as follows:

- Given the acquired knowledge about the use of Neuroscience and the use of EEG, Hu M. et al, advised to collect more quantitative methods and tools to study human's response, especially related to the built environments. Moreover, they highlight the need to examine further parameters such as light, colour and views[19].
- The broad usage of Immersive virtual environments (IVEs) does not offer a strong level of consistency of human response data across identical real and virtual environments[21].
- Another raising quest is how to quantify the difference between Reality and Virtual Reality, under both daylighting and electrical lighting environments and the impact of physiological responses.

The above-mentioned recognized gaps are critical in our research, and although it is not possible to address them extensively, it is the author's aim to propose an investigation that could give tangible approaches to such topics.

The identification of these suggested gaps in the current state of the knowledge has also led to a driving vision for the current master project and consequently the research hypothesis as well as the research question to address the present investigation.

3. Research Question and Objectives

Based on the thorough literature review, the outcomes of the identified gaps in the current state of the knowledge, it was possible to delineate the aim of this study which is to determine to what extent is possible to link the non-visual effect of light to the brain activity.
In addition, further experiments and tests seek to establish the level of perceived realism conducted on the VR experience, while also measuring through subjective assessments, the activated emotions. After all, the formulation of a research question will act as a guiding light that leads the following investigation on a path to tackle our intentions and understand how the hypothesis can be addressed while also demanding a conclusion to itself after a thorough evaluation of the research project.

3.1 Research questions

This master thesis aims to answer the following research questions, which have been formulated as follows:

- *"How can a Neurophysiological approach unveil the pattern of the circadian influence in both real and Virtual environments?"*
- *"Can Virtual Reality offer a level of Realism such that it could evoke positive emotions?"*

3.2 Objectives

To tackle the first research question, the main objective of the authors is to examine and probe whether the recommendations during the daytime of 250 melanopic EDI lux, generate a possible correlation with the measured brain activity during given light scenarios.
The mean value of the contribution of both daylight and electrical lighting will be evaluated along with the different waves resulting from the recording of the EEG, while also trying to perform statistical analysis.
Furthermore, once every EEG detection is collected for the number of participants involved, quantifying arousal and valence will give a comprehensive understanding of the emotions.

Lastly, to answer the second research question, the focus will be to build a realistic, light-based environment in the VR, to try to mimic the real setting, possibly considering some sort of interaction and evaluating the experience through questionnaires and subjective assessments, while also analyzing the activity of the electroencephalography and comparing it in between the two conditions.

4 Method

The following section will explain concisely and discuss thoroughly the structure of the methods and theories being used in this Master thesis; from the brief fundamentals of the project, the pilot test being conducted to the main focus of the formulation of the driving vision and the formulation of the research question.
Through the process, all the different sets up for both quantitative and qualitative analyses have been carried out, declaring which instruments were used to achieve the measurements, the methods used to obtain the results, the procedure for conducting the tests or the experiment and any other relevant resource that has been used for the purpose of the project.

As a first step, to evaluate and possibly, verify the initial premises of cross-disciplinary methods, such as the above-mentioned combining a Neuroscience approach together with the integrative design mixing lighting perceptual experiences in both real environments as well as virtual environments, a pilot test has been conceived. This latter appeared as the unique way to evaluate the premises after the findings of the gaps in the state of the knowledge; the pilot test used an "Explanatory Sequential" method, as the aim of the early stage of the test, was to seek in between the quantitative data gathered a possible correlation between circadian metrics and the different channels band frequencies given by the EEG.

As the pilot test is being conducted and carried out, significant results and findings, as well as not properly pursued methods, could be outlined, so that it can be possible to set up a new experiment, based on the results previously obtained and adjusted on the new findings and needs. Overall the methodology employed in the current project wants to find, by pursuing and analyzing different sets of data, information to connect the pattern of human circadian rhythm, to the related brain activity, experienced in two different environments with the same conditions of lighting. Thus the vision suggests, an interest in unveiling patterns that humans experience in an interior space, such as an academic environment, is of primary importance, firstly to address the well-being of inhabitants as it is believed to have a strict connection between what the eyes get from light and how the brain records the experience of it.

After the pilot test was carried out, a convergent mixed method was used; that is why some of the outcomes seemed inconsistent without any qualitative data. The collection of a vast amount of raw data could give valuable answers to whether correlations or differences may occur; what is more, gathering at the same time qualitative records, allow the research to be more complete.

4.1. The Pilot Test

As already discussed previously, a preliminary pilot test was conducted, in order to seek the feasibility and a brief evaluation of the proposed design vision.
The focus of the test was to assess the pattern of the circadian rhythm, as measured with the chosen metric of *mEDI,* melanopic equivalent daylight illuminance, which is recommended by CIE[31] for studying the non-visual effects of light, in conjunction with a neuro-scientific approach using an EEG headset, to gather the brain frequencies throughout electrodes and so the related emotions.
The test sought to evaluate the intentions by comparing the same settings in both real and virtual environments, by analyzing two sets up appraising the contribution of daylight and its perception in the space and the real contribution and the electrical lighting either.

Regarding the space, the choice for this initial test was redirected to a public and accessible space within Aalborg Universitet København, due to the easy access to rooms mostly all over the campus. For this reason, The Lighting Design Office was chosen due to the familiarity of the space the authors of this manuscript. The thorough information available at the time, such as the materials, dimension of the space and placement of the luminaires, made it possible to establish the pilot test.

The 3D model of the Lighting Design Office was already created for a previous project, using Rhinoceros[32], a computer-aided design software which allows users to create, edit and render NURBS curves (that is an acronym that stands for *"Non-Uniform Rational B-Splines"*), which are a perfect mathematical representation of geometries.
Afterwards, the complete model was then uploaded on Twinmotion[33], where all the materials have been applied with the ultimate purpose of matching as closely as possible to the real environment. As far as the lighting conditions were concerned, the setting on the software aimed to replicate the product's technical specifications as shown below in Table 1.

Table 1 Table showing the product specifications of the existing luminaires

Product	***Lumen Output***	***Power***	***CCT***	***CRI***
XLN 600 XC	4200 *lm*	30 W	3000 K	> 90

Thirdly, the 3D model was opened in Rhinoceros through an original plug-in called ALFA[34]; the software is able to perform simulations about the non-visual effects of light thus at this stage it will be meant for obtaining circadian values in the virtual environment.
Every geometry was then categorized in materials at a later time in ALFA to match the reflectance values of the existing materials.

4.1.1 ALFA

ALFA, an acronym that stands for "Adaptive Lighting for Alertness" is a software plug-in that runs on architectural and product design 3D modelling software Rhinoceros.
The software runs to predict simulations about the non-visual effects of light by giving as a result equivalent melanopic lux (EML). ALFA uses an extended Radiance lighting engine to perform calculations, which has been extended for the purposes of these computations to a high resolution with 81-colour spectra channels. One can grasp the possible differences that occur between the real and virtual environments, although the second case, does not strictly relate to the visualized VR product, as the EML strongly depends on the light emitted
by a luminaire or the sky. Therefore the objective of this analysis will only aim to evaluate the space and luminous conditions within the virtual environment.
However, an estimation of the amount of light absorbed by the photoreceptors of an ideal viewer will be obtained, in the form of EML or the accepted and recognized metric of mEDI.

The software offers a library of high-resolution source spectra, and the possibility to upload real photometric data, for instance, *IES* files.
Before the calculations, the software demands to set some crucial parameters:

- *Location*: one can enter the coordinates of Latitude and Longitude
- *Time*: enables the user to select the date, month and time of the day
- *Sky Condition and Ground spectrum*: the user can choose from four different types of sky conditions, (Clear, Hazy, Overcast and Hard Rain and Cloud) and seven types of ground spectra: uniform, seawater, deciduous_forest, dry-grass, green-grass and snow

Every geometry was then categorized in materials at a later time in ALFA to match the reflectance values of the existing materials. Finally, the placement of the luminaries completed the setting, for evaluating the virtual environment, with a calculation grid, at floor level consisting of three positioning points.

4.1.2 Twinmotion

Twinmotion is a real-time visualization software that enables architects, designers, and other professionals to make changes to their designs and see the results instantly. When used with VR, this feature becomes even more powerful, as users can make changes and see them in real-time within the immersive environment. It also allows us to create immersive 3D environments quickly and easily. When used with VR, Twinmotion can provide several benefits, such as providing an Immersive experience, as it allows users to experience a virtual environment and moreover, it enhances the collaborations between professionals and work together making collaboration more efficient and effective.
Overall, using Twinmotion with VR can enhance the design process by providing a more immersive and engaging experience, enabling real-time design changes, improving communication with clients and stakeholders, and facilitating collaboration among team members.

After the office model was made in Rhinoceros, it was then imported through the plugin, to allow the details to be made in the program, especially the light to be as close as possible to the real environment of the lighting of the office.
Materials also were imported and consequently, to stick as much as possible to the reality, efforts were redirected to match the right HDRI picture for an overcast sky to match with the physical one.
Twinmotion has a big selection of IES lights and all the different settings for changing CCT, lumen output and shadow patterns of the lights making a great instrument and being able to show lighting design propositions and ideas.

For the purpose of this pilot test, it was used as a VR headset, the Oculus Quest 2[35], which has an all-in-one design that eliminates the need for external sensors or a PC.
In addition, it has a high-resolution display with a resolution of 1832 x 1920 per eye, resulting in sharper visuals and a more immersive experience.

4.1.3 Unicorn Hybrid Black

To acquire raw EEG data, a Unicorn Hybrid Black[36] headset device was used after an introductory workshop at Augmented Cognition Lab. It allows us to obtain signals from the human body, through the acquisition of eight electrodes of complete 8-channel EEG.
The Unicorn Suite is the software environment, consisting of standalone applications and APIs to interface the Unicorn Brain Interface, acquire and process data and perform BCI paradigms. The wearable headset tracks EEG data from the electrodes, sampled with 24 bits and 250 Hz per channel. To record brain activity, the Unicorn Hybrid EEG disposes of a Bluetooth connection and a software suite that includes the Unicorn Recorder Bandpower.
The electrodes are applied in four different positions, as Figure 3. shows, and all of them are made of a conductive rubber that allows you to record with a conductive gel lastly, the reference and ground EEG electrodes are fixed on the mastoids of the user.

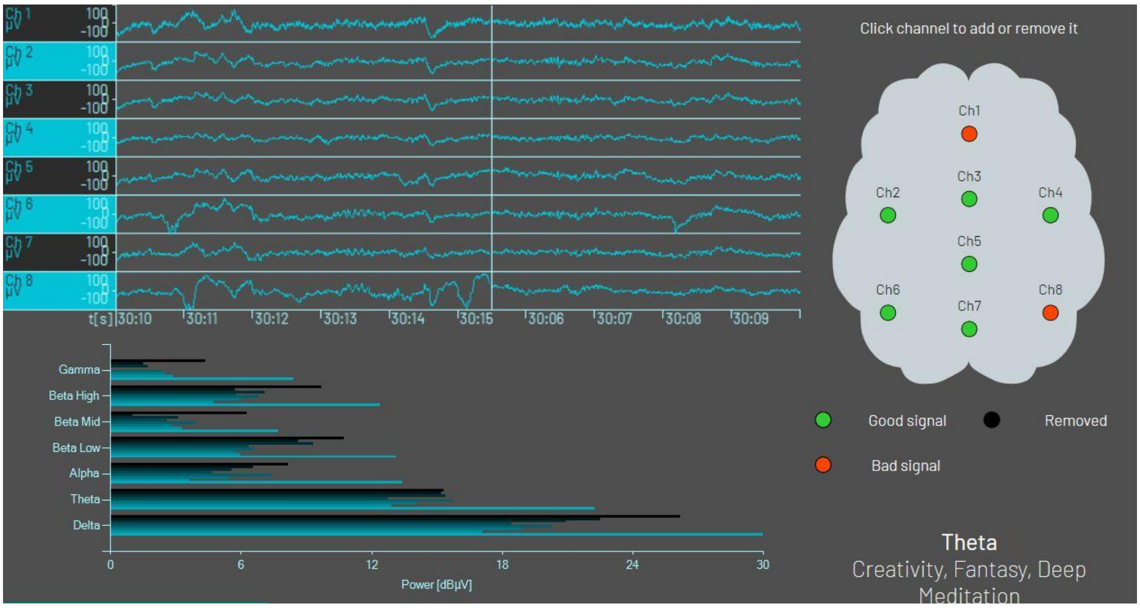

Figure 3. The Unicorn Bandpower software allows tracking the 8 channels for the brain activity of a user. On the left the frequency for each channel is reported and on the right the position of the electrodes. A screenshot obtained from the software by the authors

4.1.4 Procedure

For this initial and exploratory pilot test, the authors have invited five participants; subjects were contacted briefly before the start of the pilot test and invited into the Lighting Design Office space and once there, they have been instructed about the whole procedure and the concept, as well as the purpose of the test (Figure 4.).
The pilot test took place in the Lighting Design Office, over two days, the 2nd and the 3rd of March 2023. Participants were asked to sit on a chair and one of the investigators was able to put on the subject's head scalp for EEG; to do so he needed to make sure that all the pins inside the scalp were redirected correctly so then he could attach the conductors for the channels. As a last stage, a conductor gel was inserted in the holes where the conductors were attached, throughout a syringe, by making sure that all the pins inside, in close contact with the head skin, were correctly sprayed with enough liquid.

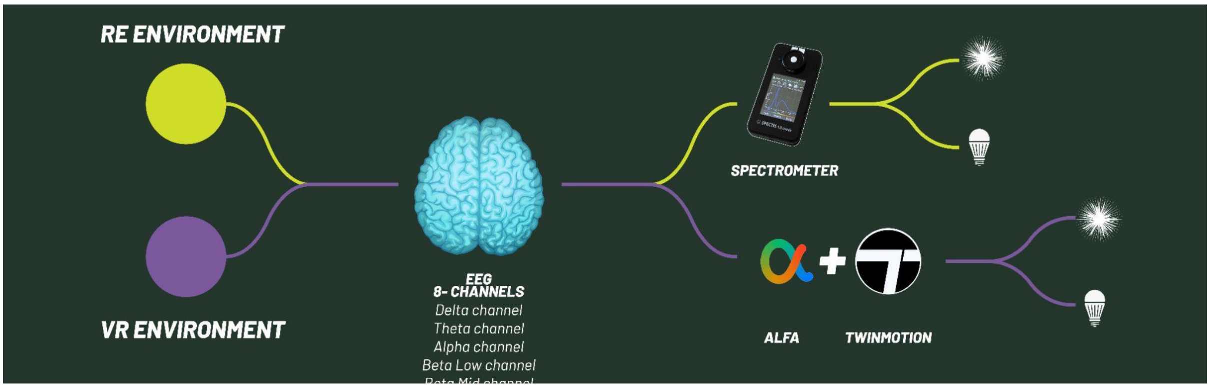

Figure 4. Pilot test protocol, highlighting the two different ways to evaluate the premises: EEG will monitor the brain activity for the real environment (RE), while a spectrometer will be used to obtain mEDI values and at the same time, for the virtual environment the same setting and condition will be evaluated with ALFA and Twinmotion to run the VR. Graphic self-produced

Once all the conductors were placed, the investigator ensured the stability of the EEG signals, waiting for the "green status", which ensured a good signal before the start of the EEG record.
At this point, the test could start and the participant experienced through the visual stimulus of two lighting conditions, the perception of the room:

- The first lighting condition was the sole daylight situation, to be experienced in three different positions in the room: the first one towards the entrance, the second one in the middle of the room and lastly, close to the glazing area. Figure 5. shows the three assumed positions and the unique direction of view.
- The second condition comprises turning ON/OFF the lights in the office, making it possible with a portable switch that could control all the electrical lighting.

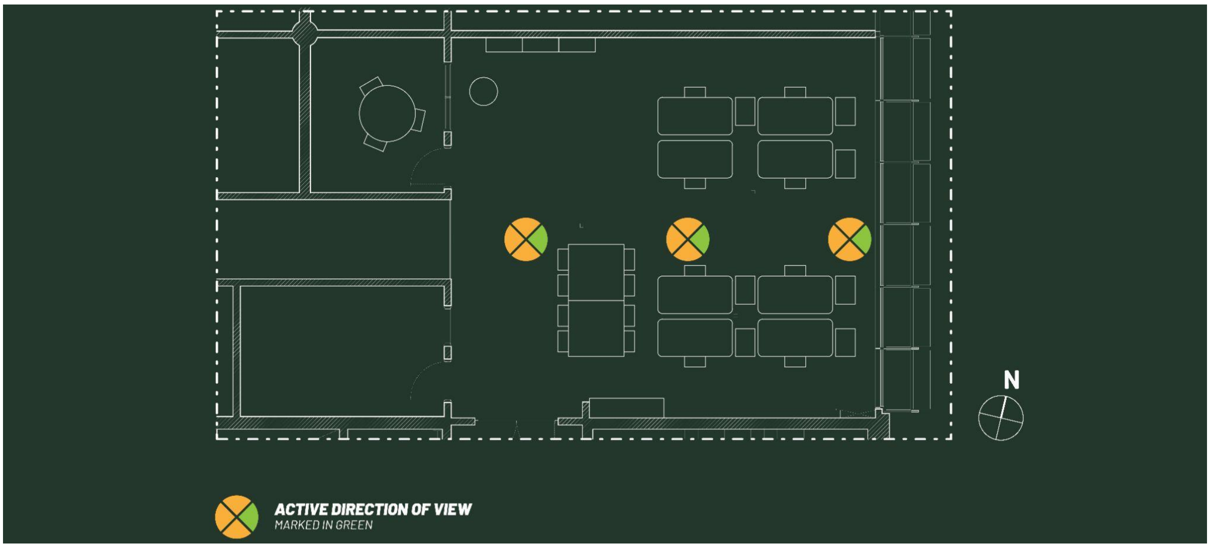

Figure 5. Floor plan of the Lighting Design Office, showing the three positions for the pilot test and the considered direction of view (marked in green). Graphic Self-produced

A camera tripod has been used along with the spectrometer GL SPECTIS 1.0 Touch + Flicker, mounted on it, which was able to obtain mEDI; the height for the detections was set to 1,2m above the floor, to configure the ideal point of view of, as specificated by Brown et al[37].

After all the settings of the different equipment and the certainty of the stable connections between devices, the test could eventually start.

All participants experienced the light conditions, while recording EEG data, for 1 minute each, being assisted in the change of position by one inspector and for almost 5 minutes to experience the VR scene, for the whole length of the test of ten to fifteen minutes.

Lastly, each of the participants was helped to remove the VR headset, the electrodes and the scalp of the EEG device.

This exploratory pilot test focused only on the evaluation and analysis of quantitative raw data, both from the spectrometer and the EEG headset, gained from the experiment. In the following paragraph, a brief explanation of the preliminary outcomes and limitations will be discussed.

Figure 6. ***Left (a):*** One of the participants, wearing the EEG scalp with electrodes connected, experiencing the daylight scenario and electrical lighting; the spectrometer measuring the mEDI has been placed in front of him/her; ***Right (b):*** One of the participants, wearing the EEG and the VR devices, immersed in the VR reality of the space, experiencing the daylight and electrical lighting scenario. Photos shot by the authors

4.1.5 *After the Pilot test*

In the current section, a brief explanation of the early outcomes and results from the preliminary pilot test, will be provided; in addition, the terms, limitations and possible implementations, will be discussed in another paragraph.
As already touched upon in the previous chapter, the pilot test was carried out across 2 days with a total of five participants, in which EEG records, mEDI detections and VR scenes were deployed; from the early trial, the results were first analyzed to establish a correlation between the circadian metric of the melanopic equivalent daylight illuminance and the brain activity. For this stage's sake, all eight channels have been considered for the analysis, to find which one was more appropriate for further evaluation.

4.1.5.1 Outcomes

It is relevant to declare that all the results from the EEG were started and stopped for the length of the test; subsequently, every recorded file was saved as an Excel file for each participant. The Unicorn Hybrid Black software automatically provides the data as "band power"" for analysis of the different brain wave frequencies by collecting 25 samples per second. Overall, the total amount of columns of data was 70 columns and each stands for the data from the 8 channels connected to each participant's head.

Towards simplification during this phase, the analysis took into consideration the averaged channels, (automatically averaged by the software) for each wave:α (alpha), β (beta: - low, - medium and - high), δ (delta) θ (theta) and γ (gamma).

All the different records from the EEG have been compared to three positions of both the daylight scenario and the electrical lighting scenario, in regards to the real environment; the same procedure has been applied to the virtual environment, by gaining the EML values from ALFA, which then were converted to mEDI, according to the following formula[38]:

$$EML = 1{,}104 \times EDI$$

The obtained results are distant from each other and do not depict a linear case; by first examining the Real environment, the following results could be summarized, in terms of an existing positive or negative correlation between mEDI and the whole brain activity:

- Participant 1 shows a ***negative*** correlation for the daylight scenario, whereas presents a ***positive*** link with the electrical lighting scenario.
- Participant 2 revealed a ***negative*** correspondence for the daylight scenario but a ***positive*** link for the second scenario.
- Participant 3 proved to have ***positive*** correlations for the two scenarios, although close to the *zero*.
- Participant 4 shows a ***negative*** correlation for the daylight scenario and a ***positive*** link for the second set.
- Participant 5 manifested to have ***negative*** correlations for the two scenarios.

On the other hand, as far as the comparison with the virtual environment is concerned, all the participants reported negative correlations between the methods.

Furthermore, another differentiation sought to highlight, by analyzing the whole brain activity from the 8 channels, which of the two scenarios resulted to be the most elicited and preferred by the participant. In this direction, each of the waves has been recollected and averaged together, and all the differentiated positions considered, for the two scenarios and compared together; following the results are presented briefly in the form of a percentage of the major activity:

- Participant 1 reported **100%** of major activity for the Virtual Environment for the daylight scenario, and **57%** for the VR in regards to the second scenario.
- Participant 2 showed **57%** of higher mental activity for the Real environment for both of the scenarios.
- Participant 3 manifested the first significant discrepancy as ***85%*** of greater functioning for the VR in regards to the daylight scenario, and ***71%*** for the RE for the second scenario.
- Participant 4 linked the ***85%*** of bigger entrainment for the real environment for the two scenarios and conditions.
- Participant 5 scored **71%** of major activity for the Real Environment for both of the scenarios.

Overall, all things considered, by aggregating all the values in an average, it could be highlighted that participants had relevant elicitation of the brain activity in the Real environment with the 55,7% as opposed to the 44,3% of the virtual environment.

4.1.5.2 Limitations and Implementations

After having analyzed the preliminary outcomes of the pilot test, the different procedures carried out during the period and the methodologies being adopted, some limitations could be highlighted and consequently, an implementation is being proposed for a better direction in further experiment.

In regards to the obtained correlations, whether negative or positive, between the melanopic EDI and the brain activity, it seems inconsistent to make a comparison, due to the limited number of measurements detected by the spectrometer. The three measurements have been taken at the beginning of the EEG record, therefore they depict a restricted time to compare with the signals. A proposed solution would be triggering continuous and serial measurements from an automated function of the spectrometer, so the same period of mental activeness

As experienced, when applying the VR headset on the participants' head, over the EEG scalp, it was not conveniently possible to secure the VR device, thus the investigator helped to keep it in position. Integrating the traditional EEG caps with the straps and harnessing the VR headset in a way that did not further add any discomfort to the participants.

No questions have been submitted to the participants, at the beginning of the test, to verify if caffeine, alcohol or other substances were assumed. Those could have possibly altered the whole brain activity. Furthermore, a participant reported suffering an intense toothache on the day of the test. An introductory set of questions will evaluate possible conflicting aspects regarding the test.

No self-assessment nor subjective questionnaires have been presented to the participants to seek the level of presence and perception in the virtual environment. After the comprehensive and extensive literature review, a thorough set of questionnaires to evaluate the intentions will be proposed in the final experiment.

It has been highlighted as a "cartoon effect" of the entire VR experience. This might be linked to the performances of both the laptop being used and Twinmotion.
The plan is to investigate another Render engine that could give better lighting simulations and a better level of realism, along with a more performant CPU desktop.

Lastly, a control, to supply a base comparison for the results is required among the EEG data. This will be shown to each participant at the beginning of the experiment but also in between each light condition and scenario, thus providing a new "baseline" measurement for each condition.

4.2. The Final experiment

To address the impact of the non-visual effects of light, by studying it in two different environments, the real and the virtual and measuring and quantifying the relations with the brain activity, a pilot test has been conceived and carried out to verify the initial hypothesis and the vision. Once the first test was performed, this led to the implementation and planning for a new experiment which sought to compare, quantitative and qualitative methods. The measurements on the field, that have been considered, were both mEDI and EEG raw data, the tracking and mapping of the concept of valence and arousal and subjective assessments for perceived presence and realism, as well as subjective questionnaires simulations with the purpose to find a possible and reliable way, to explain how our brain will act in these two realities under certain lighting conditions.

The final experiment was set to be performed on week 15, from the 10th of April, until the 14th of the month.

4.2.1 The Space

The main focus of the mentioned experiment is directed at office space, within a working period of a minimum of 8 to a maximum of 10 hours.
Since the first test was carried out in the Lighting Design Office, located in the Building A of Aalborg University Copenhagen, with all the related implications for may cause disturbance to the inhabitants of the space, the choice for a new space was set on the DDL Lab in the Building B of the same campus.
DDL stands for "Double Dynamic Lighting" which was used by Hansen et al. to study the impact and the qualities of the *flow of light* on workers in an office space[39].
The room seemed to suit the aims and objectives of the experiment, because it provides a combination of daylight and electrical lighting in the same environment, which is believed to create diversity in the perception of the space, as well for the same condition replicated in the virtual environment.

The room is oriented towards the southwest with two windows and is located on the third floor with no critical obstacles blocking the daylight inflow.
The office dimensions were obtained by manual measurements with laser tape and consisted of a 4.4x5 meters room, with a height to the ceiling of 2.6 meters. The space consists of four workstations, completed by four desks and chairs, two cabinets, two blackboards and a pair of TV screens. To have clean and good management of the room, some chairs, the blackboards and the TV screens were kept out of the space.

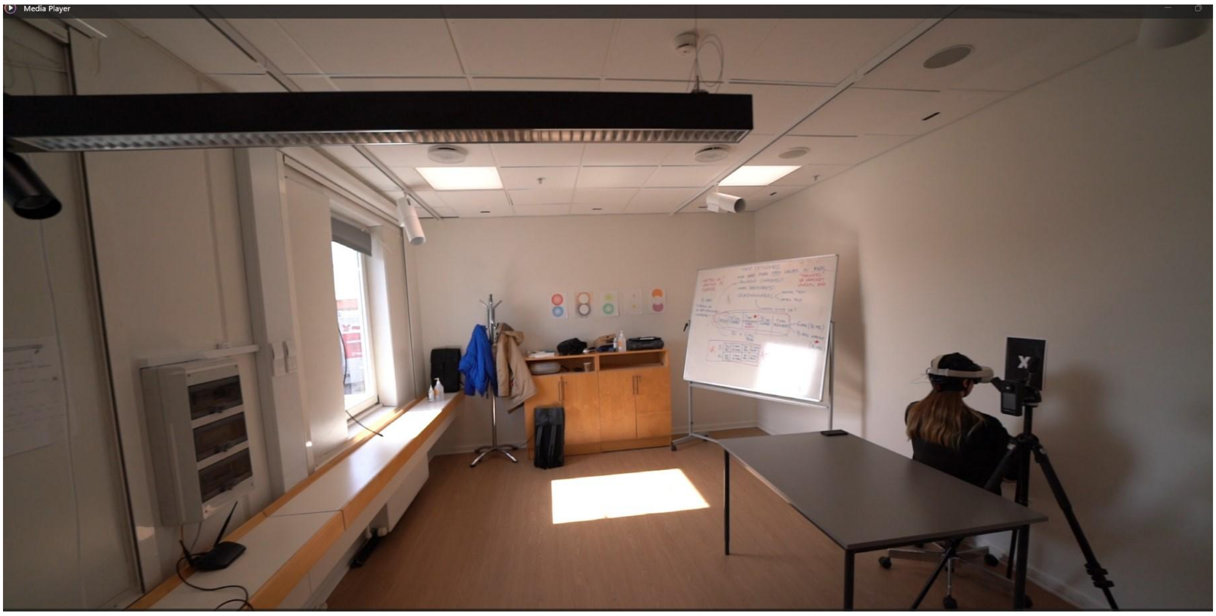

Figure 7.: The Double Dynamic Lighting Lab, as appearing during the first day of the experiment, with one of the participants (on the right).

4.2.1.1 The Lighting in the DDL

A comprehensive analysis of the existing electrical lighting is of particular importance, especially for the intentions to replicate the real conditions in the virtual environment; therefore, the intrinsic properties of the luminaries could help to achieve so. To know the exact placement of the lights, some manual measurements were performed to finally draw an editable dwg file with the position of the luminaries. The composition of the ceiling facilitates the whole process, as the office is built under a regular grid of 60x60cm and the square luminaries are ceiling recessed. The whole equipment comprised three types of luminaires, and for the objective of this experiment, only one type has been taken into consideration.
Specifically, the Fagerhult Multilume Flat Delta[40] was used, as it is a tunable white luminaire that varies its CCT in a range of 2700 to 6500 K, with a maximum luminous flux output of 3537 lm. The electrical lighting is controlled by a DALI and it is possible to freely control the luminaries through a mobile application that runs on Zumtobel's Litecom lighting-management system (LMS). The app had already saved the preset for some predefined scenarios, therefore to control only the desired lights access to the specific IP server was required.

4.2.2 Participants

For the purpose of the experiment fifteen (n=15) were recruited to give their contribution by measuring through an EEG headset, their brain activity while being tested in different lighting conditions in both the real and the virtual environment.
The participants, with an overall average of 29,86 and a standard deviation of ±5,38, were aged between 23 and 46 years old, (53%) in a range of 24-30, (33%) for the group of 30-36 and (7%) for both 18-24 and +42 years old. The whole sample of them had educational levels, ranging from Bachelor to Master and 66% was active and enrolled student at Aalborg University at the time of the experiment lastly, a sample of 66% was male and 34% (72%) and PhD (6%). The

participants were invited by the authors of the experiment to join the test on week 15 of 2023 and according to their availability, the eligibility was agreed. A doodle was created and sent to the sample size to fix the appointments and the preferred schedule. Some of the participants were enrolled in the MSc in Lighting Design so that they could be familiar with most of the topics being treated in the experiment. This might have caused some bias that possibly could have been solved with an introductory set of questions about the perception of lighting conditions before the start of the experiment.

4.2.3 The Equipment

As mentioned before, as an EEG device it was used as a Unicorn Hybrid Black that uses 8 channels sampled with 24 bits and 250 Hz per channel. The scalp was placed on the participant's head, followed by the conductive rubber pins and finally the electrodes. The Bluetooth connection made it possible to connect and record the activity onto the program.

Once again the spectrometer *GL SPECTIS 1.0* Touch + Flicker was used for its capability to measure light, in addition to the extensive range of standard photometric and colourimetric values, as well as to obtain circadian metrics. The tool needed to be calibrated based on a completely flat spectrum and 0 lux before each measurement; to do so, the device was positioned in its case while running the calibration. The spectrometer was later mounted on a tripod with a tilted head, positioned perpendicular to the floor and adjusted in height according to an observer's view, set at 1,2 meters above the floor. It was later set to trigger continuous measurements without touching it, thanks to an in-built firmware.

The VR headset used in this study is the Oculus Quest 2 features a high-resolution screen with two separate displays with a refresh rate of 90Hz, one for each eye and it was chosen among other products because it provides users with sharp, clear visuals that enhance the immersive VR experience. The Quest 2 also features adjustable lenses that can be moved closer or farther away from the eyes to accommodate users with different eye distances, which helps to reduce eye strain during extended VR sessions. The headset is capable to log-in automatically to a WiFi connection or through a connection via cable.

The virtual environment experiment should have run on a more performative system so that a desktop Workstation with an Intel R core i7-11700F processor was used, comprising an NVIDIA GeForce RTX 3060 Ti graphic card, with 16GB DDR4 RAM.

4.2.4 Questionnaires

A mixed-method research approach combines qualitative and quantitative methods in the same study. In this present research, by including that, a rich insight into the phenomena investigated and the opportunity for stronger justifications could be offered.
The questionnaire items for perceptual and level of realism impressions were based on the work of Chamilotori et al. and all the different questions were grouped according to the procedure of the experiment, meaning that the set of questions about the investigation of the perception in regards to daylight was coming first, followed by the SAM range of evaluations,

where the range was set from 1 (=low valence/arousal) to 5 (=high valence/arousal) considering a score of =3 as neutral. The second part of the experiment is the evaluation of the Virtual experience followed by considering questions about the perceptual accuracy of the proposed VR space and the participant's perceived presence. Dimensions such as pleasantness, level of acceptance of the existing lighting conditions, visual interest, and complexity, with the addition of a question about the performance regarding the activity and a final sum-up questions to seek any differences between the two environments.
Introductory, as well as conclusive questions followed the same structure, with possibilities to answer with open questions.

4.2.5 The Virtual Process

After finishing to model in Rhinoceros 7, on a Windows laptop, to later on perform and assess the simulation with the plug-in ALFA. The DDL Lab was so modelled recreating the essential and basic geometries that comprise approximate dimensions of 6 meters x 4 meters. Only the tables were re-created for the calculations in ALFA, whereas more advanced and detailed models were added for the Virtual Environments.
Once the whole process of the 3D model was concluded, the file was passed through a plug-in into Twinmotion to apply the full textures. Subsequently, it was imported into Unreal Engineing the Datasmith Plugin, so that the model, materials and textures were preserved.

4.2.5.1 Unreal Engine

After the outcomes of the pilot study and the feedback received, literature research was conducted to seek a better render engine to offer a higher, more immersive and close-to-realism experience. The review was consistent in highlighting Unreal Engine 5. It is important to state that as a software it was free to download and most importantly, it was developed with an interactive system and ran daylight simulation. One of the features that were in line with the aims of this project is the lighting algorithms that UE5 uses; there are built-in algorithms on physically based shading, which correctly simulate the interaction between light rays and surfaces using the inverse square law, including light-material interactions. Furthermore, Unreal Engine takes advantage of a set of physically-based lighting units, such as the Bruneton Sky model[41] and other accurate sky models are supported.

The global illumination algorithm in the Unreal Engine is used to automatically produce lighting illumination scenes and calculate detailed shadows at runtime[42].
Moreover, the introduction of Nanite, which is a virtualized geometry system which uses a new internal mesh format and rendering technology to render pixel scale detail and high object counts, gave considerably higher advantages such as the level of detail that is automatically handled[43].

4.2.5.1.1 The Lighting

In order to create realistic lighting with Unreal Engine, a feature called Dynamic Sky was utilized. This allowed us to adjust the position, angle, and intensity of the sun to simulate different lighting conditions such as sunrise, sunset, midday, or cloudy skies. Additionally, this feature simulated atmospheric effects like haze, fog, and clouds to enhance the realism of the outdoor environment. We also enabled Nanite and Lumen to produce more accurate and realistic results in the VR experience.

On the other hand, the electrical lighting was created using an ambient light source to replicate the four light sources present in the real environment as closely as possible to reality. The exact colour temperature value was set in the program to ensure accurate colour reproduction. To further enhance the realism of the lighting, we created a new emissive material in Unreal Engine for the glass material in front of the light source, which produced a glowing effect. The electrical lighting was set to one candela per light source when the light was on. Overall, by utilizing these features of Unreal Engine, the creation of a virtual environment with lighting that closely resembles the real environment, provided a more accurate and immersive experience.

4.2.5.1.2 Lumen & Nanite

The feature that stands behind a correct and accurate lighting calculation in the software is called *"Lumen"*, which is a global illumination system that calculates indirect lighting in real-time, allowing for more accurate lighting in dynamic scenes. Moreover, it also includes features such as ray tracing and reflections, which further enhance the realism of the lighting.
For instance, when the activity was shown to the sample of participants, they experienced the moving objects in the scene, while the lighting was adjusted accordingly, providing realistic shadows and reflections.
One of the main advantages of using Lumen is that it simplifies the lighting process by removing the need for pre-computed lighting. This makes it easier to create dynamic and interactive scenes that respond to user input.
Lumen also supports various features such as global illumination, reflections, and soft shadows, which can greatly enhance the visual quality of your scenes.
The combination with Lumen and Nanite from Unreal Engine 5 made it possible to have way better results and enhance the virtual experience to the most with the existing equipment.

When nanite was presented in the previous paragraph, it is essential to declare Nanite is a powerful tool that creates millions of high-resolution geometry meshes, where the geometry is broken down into micro polygons with a minimal performance impact. Combining the Nanite and Lumen together, the whole procedure became noticeably more realistic and more accurate.

Figure 8. The actual room recreated in the virtual environment during the daylight situation

Figure 9. The virtual room, modelled and with materials applied and presented in the second scenario during the daylight situation and electrical lighting altogether.

4.2.5.2 ALFA

Once the 3D model of the DDL Lab was created, the command "ALFA" was recalled in Rhinoceros to launch the program. The actions needed for preparing and completing the scene before performing the calculations were respectively: set up of specific parameters such as geographical and time related, for instance, the date and hour of the experiment at different time slots. Crucial and essential parameters were "*Sky Condition*" and "*Ground Spectra*" which significantly changed the scene, according to the real changing of the daylight conditions. Following the step of assigning the materials to each geometry in the 3D model, from the existing ALFA predefined material library, with laboratory calculated values of specularity, photopic and melanopic reflectivity. Prior to this, manual measurements with the lux meter *Voltcraft MS-200LED SE* (accuracy + 3%) were detected for later comparison to the library and matched to the closest level of the obtained values of the reflectance. The values are presented in Table 2 below.

Table 2. The layout of the DDL Lab was created in ALFA, with the position of the point for the calculation and the directions of view assumed as well as the placement of the luminaries. **The glass reflectance value was not possible to correctly measure due to the not-fully opening window.

Element	*Name (Experiment)*	*R/T photopic (luxmeter)*	*Name (ALFA)*	*R/T photopic (ALFA)*
Walls	*White painted plaster walls*	*66%*	*White painted corridor walls*	*79,8%*
Floor	*Wood laminate flooring*	*29%*	*Interior Flooring*	*38,1%*
Ceiling	*60x60 square panels*	*84%*	*White painted room ceiling*	*82,2%*
Window Frame	*White painted wooden frame*	*78%*	*White styrofoam*	*84,0%*
Table	*Grey laminate*	*6,5%*	*Black Backpack*	*2,8%*
Counter	*Wood laminate*	*24%*	*Wooden textured tabletop*	*22.7%*
Door & Frame	*White laminated door + frame*	*74,2%*	*White Painted Door*	*78,9%*
Windows glass	*Double glass with insulation*	****	*Double IGU Clear Tvis 78%*	*78,5%*

The third stage was placing the luminaire and as already mentioned previously, the focus was only directed to the four (n=4) recessed square luminaries in the ceiling; therefore, four luminaries were created and placed in the same position of the reality and connected to the **.IES** file which was provided by the company and so included the spectral information of the fixture, was set to 4000K. Lastly, a calculation grid was positioned at floor level, and a unique point was created, as shown in the figure below (Figure 10.) with three directions of view considered to match a 180° field of view.

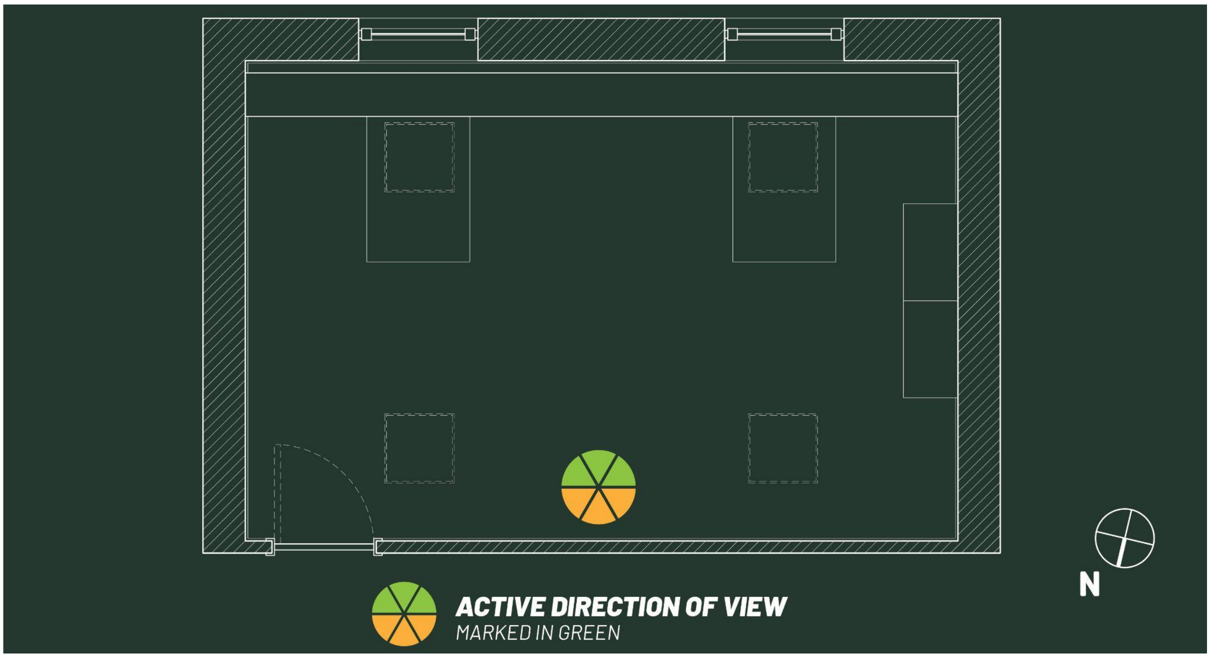

Figure 10. The layout of the DDL Lab was created in ALFA, with the position of the point for the calculation and the directions of view assumed as well as the placement of the luminaries.

After all the instruments were calibrated, 3D modelled and Virtual reality set up, the experiment could finally take place as it comprised of five phases: an introductory test survey, the Real Environment test, the qualitative assessments after the test, the Virtual Environment test followed by an evaluation either, to finally conclude with a post-test survey. The set of questionnaires was created through Google Module and got a link that was constantly sent to each participant.

4.2.6 Procedure

The experiment was conducted on week 15, from the 10th until the 14th of April 2023. There was no fixed time as the invited participants were welcome to choose their preferences between 10:00 am and 5:00 pm. Once the tested participant arrived at the room, it was welcomed to sit at the defined emplacement. After that, one of the investigators began to set up the EEG device: first, the scalp was placed on the participant's head, with the conductive plastic pins already inserted in the holes, to make contact between the electrodes and the skin. The electrodes were then attached from 1-8 channels and the conductive gel was injected throughout a syringe in the holes to spray the plastic pins and the metal part of the electrodes. Lastly, two adhesive electrodes were applied behind the ears to serve as a ground connection.
All the setup was conducted wearing sanitary gloves over the hands, that previously were accurately washed and sanitized, to guarantee the best safety and clean procedure. After wearing the EEG headset, the participant stayed still for 30 seconds to ensure that the psychological data was stable and a good connection with the electrodes was secured.

4.2.6.1 The Real Environment Process

When participants arrived in the DDL room, they were informed of the purpose, process, and precautions of the experiment, as well as their right to drop out of the experiment, especially when the Virtual Environments would come, with the chance to provoke motion sickness or any other disturbances. Then, the participants were
asked to fill in the form for the Declaration of consent to the data treatment and for the permission to take photos and videos during the process, as well as the introductory questionnaire, which included general information but also demographic questions regarding, age, country and concluding with a status check about the physiological and psychological condition prior the test.

Figure 11. *Left (a):* The injection of the conductive gel onto the electrodes of the participant's head, wearing the EEG scalp. ***Right (b):*** the control phase where the participant was asked to stare and look at the white cross on a black paper hung behind the wall.

Once the good connection with the EEG helmet was defined, the experiment started as participants were instructed to experience freely around the room, pinpointing areas of their interest, such as details, the view from outside and any other things they could have found of particular significance, for instance, if they perceived as overly bright or dark the space, any possible reflections from materials or the sun. The investigator kicked off the first task by inquiring the participator to turn around 180° towards the wall behind, where a black paper with a big white cross was hanging; this was necessary to create a baseline for the EEG data and later compare them with the other different phases of the experiment and was repeated before each stage and the task for the test person was to look straight at the white cross for 30 seconds, as a form of eye adaptation, to allow the EEG to record for 30 seconds the control phase. Subsequently, the investigator continued by verbally asking the participant to "explore different areas freely in the first scenario, connected with the sole daylighting available, by pausing if necessary areas and artefacts that stimulate your vision”. After a countdown of 3 seconds, the EEG restarted the record for 60 seconds. After this, another control phase followed and the participatory phase of the experiment could take place: on the table at which each participant sat, there were nine MDF squared laser cut pieces, 10x10cm with a number ranging from (1) to (9) written on top those (Figure 12.). The assignment was to place them, upon instruction of the investigator, in ascending or descending order, for the first 30 seconds and after that, in the remaining time, to perform the opposite duty to the one just performed, while this time six measurements, with measurements of 10 seconds from every measurement, were measured with the spectrometer. This duty was asked to be performed for 30 seconds after those the investigator passed to mix all the squares and let the participant perform the last part of the task.

Figure 12. The initial setting was placed on the table where each participant was found at his/her entrance in the DDL Lab. The lux meter was used to detect the illuminance level on the surface at each stage of the experiment in the real environment.

After the activity was finished, the second scenario of the real environment was set to begin by considering the impact of the electrical lighting. Only the recessed luminaires in the ceiling were considered as they provide ambient light with an even distribution. One of the investigators accessed the IP address of Zumtobel's Litecom lighting-management system (LMS). and individually turned on the four light fixtures, setting the intensity at full output and the CCT equal to 4000K. The experiment repeated the same process as the previous, where only verbal instructions were asked to the participant to be evaluated such as the different perception, brightness/darkness and glare conditions.

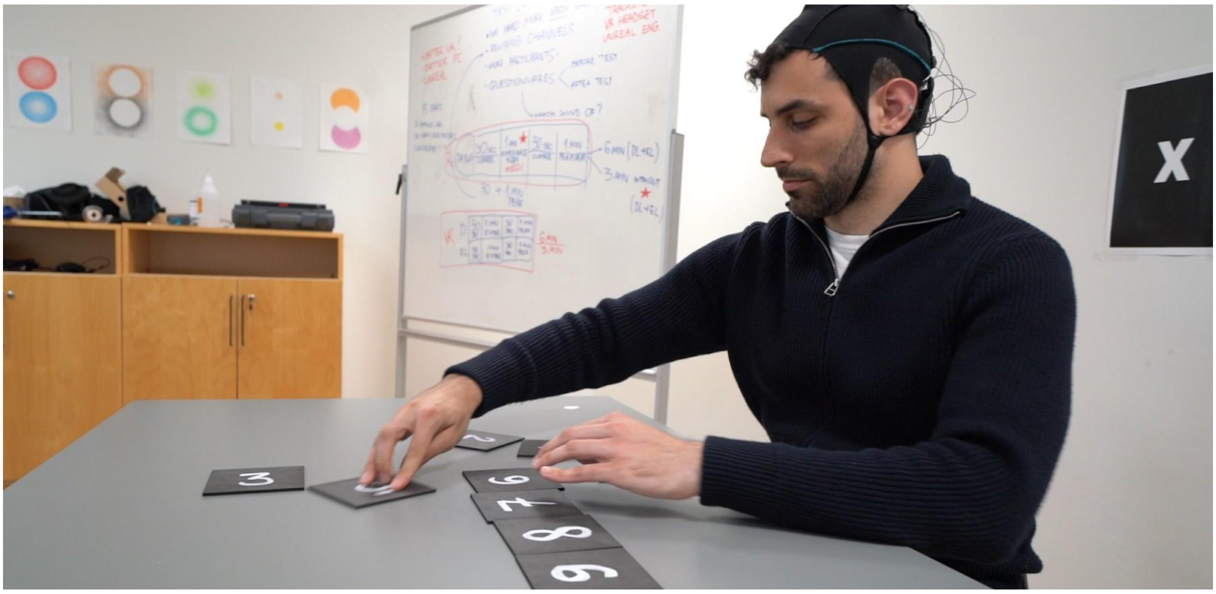

Figure 13. The performance of the activity: the participants had to dispose of, alternatively in ascending or descending order, nine little squares numbered from 1 to 9 to be completed within 30 seconds.

The overall time of the Real Environment procedure was limited to 10 min, during which researchers did not impose any further instructions on the participants. Afterwards, to conclude the first stage, the participants were asked to answer the questionnaire about the "Real Environment", consisting of questions about self-assessment evaluation for Valence and Arousal, through the SAM[44] test, as well as their level of perception of the experienced test.

4.2.6.2 The Virtual Environment Process

Once all the questions were answered, the participant was told of the end of the first phase; the Virtual environment test was the following. The VR headset was mounted over the EEG scalp on the participant's head; the participant was assisted to wear the Meta Quest 2 headset by both of the authors as the wearing was extremely delicate to avoid disconnecting any electrodes and was placed over the subject's head and arranged comfortably, providing a clear view of the virtual environment. Next, the participant was given a pair of Meta controllers, equipped with pairs of bottoms and triggers, that were then used for performing the activity.

The inspector gave directions on how to use the controllers with a brief explanation on how to grab the objects and release them, for the purpose of the activity.

Afterwards, the virtual experiment started with the first scenario corresponding to the contribution of only daylight. The control phase started as first by exposing to each member the black paper with the white cross, that was recreated, hanged and placed in the same position as the real environment. The EEG registered the brain activity for 30 seconds; consequently, the examiner instructed once again the participant by asking to "explore freely the virtual space under daylight condition, by pausing on anything he or she would find interesting and elicit good feelings' '. After a countdown of 3 seconds, the EEG restarted the record for 60 seconds.

In the meanwhile one of the examiners was taking note of the hour and the sky condition to transfer in a later stage in ALFA and perform spectra calculations for the non-visual effects.

Figure 14. ***Left (a):*** One of the participants experienced the room in the virtual environment while being recorded for his brain activity with the EEG headset mounted on his head. ***Right (b):*** the control phase where the participant was asked to rotate on herself, so in the virtual environment could correspond with the same exact position, and stare and look at the white cross on a black paper hung behind the wall.

Before starting virtually the activity, another control phase followed and introduced once again each participant to the activity that was verbally explained by one of the investigators; as it was noted in a preliminary test before the experiment started, in the virtual environment the task was simply reduced to just one. The table where the participants stood, was re-created and placed in the VR and over that, the same 9 squares were placed in the form of a box because Unreal Engine only allowed to have thick objects instead of flat. Even for this procedure, the items were labelled with a number ranging from (1) to (9) written on top of those. The assignment, prior to specific directions by the investigator, was to place them, in ascending or descending order, while being timed until the whole completion. In ALFA the experiment started approximately 20 minutes after the participant entered the room for the first time, to take into account the wearing and the setting of the EEG helmet and the real environment test as well. Furthermore, for the experience and the activity phase, since the calculation was set for three different directions of view, the calculation was performed twice at 1-minute intervals. In the end, the procedure was repeated for both the first scenario and the second scenario, and after the completion of the activity in the virtual environment, the whole experiment was declared concluded.

Figure 15. One of the participants performing the activity with the VR controllers, while being recorded for his brain activity with the EEG headset mounted on his head performance of the activity: the participants had to dispose of, alternatively in ascending or descending order, nine little squares numbered from 1 to 9 to be completed within 60 seconds.

After the subjects had experienced both environments and responded to the equivalent questions, they were asked to remove the headset, with the assistance of both the examiners and consequently the EEG device and respond to a questionnaire regarding their perceived presence, to conclude with an evaluation of their physical symptoms and conditions after the virtual experience.

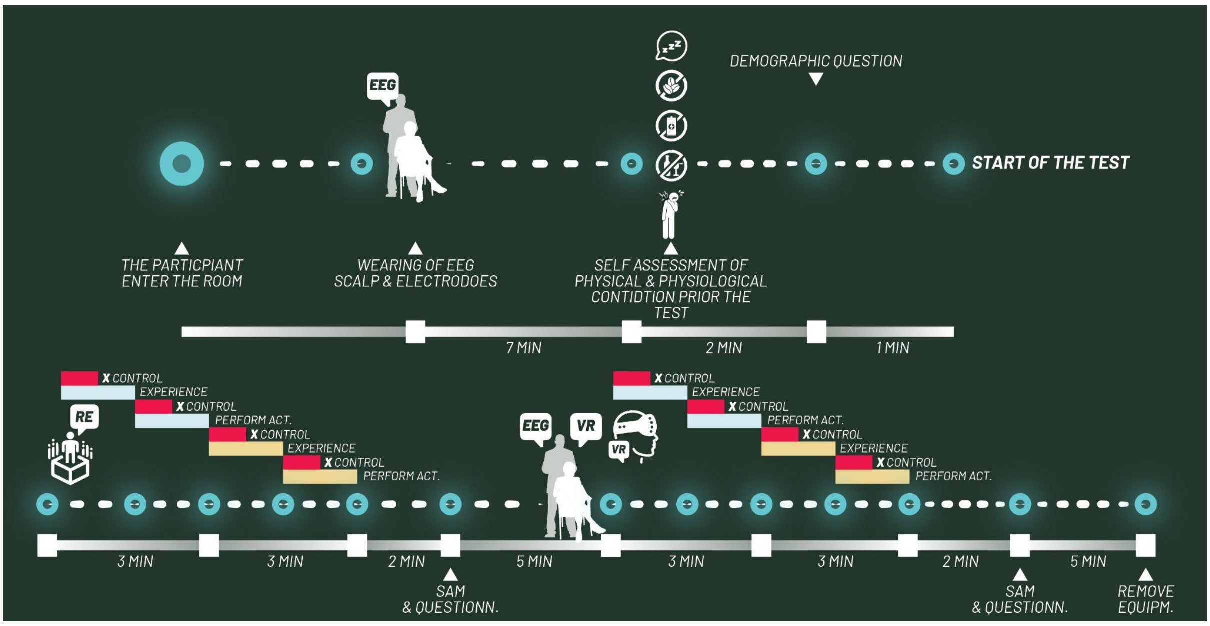

Figure 16. Graphics of all the procedures showing the first steps, through the experiment in both the Real and Virtual Environment, when indications of the questionnaire being asked.

5 Results

The results of the experimental study are presented in four sections, introducing the perceptual accuracy of the VR method (subsection 5.1), the effect of using the VR headset on the users' physical symptoms (subsection 5.2), the perceived presence of subjects in the virtual space (subsection 5.3) and the effect of the presentation order of the environment on subjective evaluations (subsection 5.4).

5.1 The melanopic response and EEG activity

In this current chapter the outcomes and findings from the experiment will be presented this section, we present the results of our analysis based on five variables: melanopic equivalent illuminance (mEDI) in both real and virtual environments, where in the former case, continuous measurements with a spectrometer were triggered during all procedure of the experiment, while in the latter case, multi-spectra ALFA was used to estimate the melanopic EDI in the recreated 3D virtual environment. Follows along the electroencephalography (EEG) where the brain activity was estimated based on the monitoring of 3 waves: alpha, beta-low, and gamma waves. The illumination conditions consisting of daylight only and daylight with electrical lighting were the tested variables for eliciting the brain activity of the individuals. This comprehensive analysis is crucial to advance our understanding of the effects of illumination conditions on human brain activity and to compare the responses in real and virtual environments. To the best of the authors' knowledge, this study is the first to investigate these variables in such depth and the hope is that it will serve as a pipeline for future research and provide a strong foundation for the lighting design field.

In this study, we compare the melanopic equivalent illuminance daylight (mEDI) values obtained from ALFA simulations of real and virtual environments. We aim to investigate whether there are significant differences between the mEDI values in the two environments and identify factors that might contribute to any observed differences. The virtual environment simulations were performed to represent a range of lighting scenarios, including daylight only and daylight with electrical lighting, to provide a comparison to the real environment measurements.

5.1.1 Comparison of mEDI between RE and VR

In this section, we compare the melanopic equivalent illuminance daylight (mEDI) values obtained from a real-world setting, using a spectrometer, and triggering to an interval of 10sec each, measurements to cover the EEG tested period and ALFA simulations of the virtual environments. For the purposes of the calculations in the software, to cover the 60 seconds periods of the monitored test, the measurements have been repeated twice with an interval of 1 minute and then averaged together.

Four stages of the experiment have been conducted, each representing a different lighting condition, including daylight only and with the addition of electrical lighting. The explanation about the comparison of the obtained values will be exploited following in the chapter and has a relevant insight to evaluate the accuracy of ALFA, even though it is not the main purpose of this investigation, and to assess the differences in mEDI values between the real and virtual environments. Results from the real, detected measurements show that the combination of both daylight and electrical has the greatest circadian effect when compared to measurements given by ALFA as shown in the graphs below (Figure 17.) which represent the different trends for mean values of all the mEDI values that were obtained at each stage for the two scenarios.

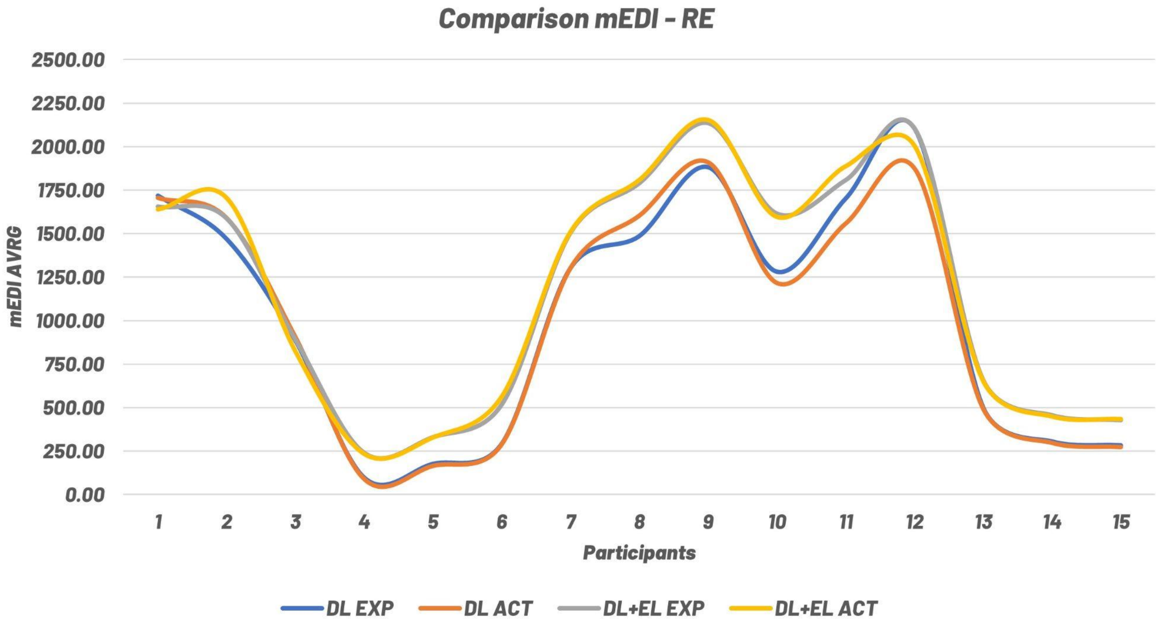

Figure 17. Graph showing the average trend of mEDI in the real environment, across the experiment period, considering the four stages and the two lighting scenarios.

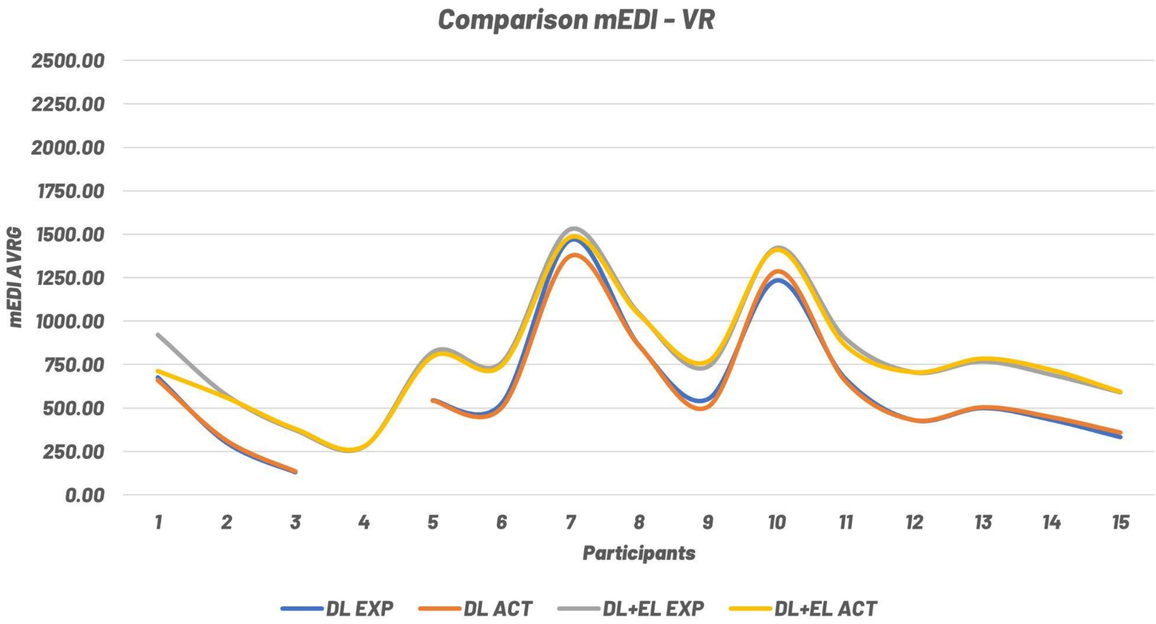

Figure 18. Graph showing the average trend of mEDI in the virtual environment provided by ALFA, across the experiment period, considering the four stages and the two lighting scenarios.

At first consideration, the curve for only mEDI obtained with daylight conditions has a generally smaller impact but notably follows the same fluctuation of the curve that illustrates daylighting and electrical lighting together, along the observed period. Overall, all the detections are above the recommended >250 mEDI during the daytime, except for some cases, for instance, What stands out in the graph in Figure 18. is that Participant 4, who was tested at 8:00 pm on the first day, with civil twilight going on, had less than 250 mEDI and so the participants of the following day when the dominant sky condition was Overcast, as well the sample of participants being tested on the last day. The peaks might reveal in some cases an excessive amount of illuminance coming at the eye level, which could be provoked due to unexpected lighting situations, such as strong reflections and glare.

From the graphs shown above, there is a substantial difference between the obtained values for the mEDI trend in the real environment and the virtual environment. The software in most cases underestimates the values of the respective stage and time of the real-world test, whereas is sufficiently able to predict and validate the measurements in terms of the capability to meet the recommendations. On the other hand, the virtual world estimated by ALFA shows significant fluctuations that are greatly distant from the other case and once again highlights the condition with both daylight and electrical lighting together as the most beneficial condition for the circadian impact. Moreover, the broad differences in values are explained by the more likely ability to have less difference of the software when estimating more stable conditions of the sky; notably, on average the reliability of the software underestimates ~400 mEDI lux with a standard deviation of ±600 mEDI lux which is considered excessive.

5.1.2 Comparison of EEG Activity

Besides the resemblance of mEDI, the EEG data collected during the four stages of the experiment in both real and virtual environments were also analyzed. Specifically, the focus was redirected on the patterns during each stage of the experiment, the two lighting conditions, fluctuations across participants and activity of alpha, beta-low, and gamma waves. When comparing the first stage, connected to "control-experience", values were obtained from paired mean values from each stage and revealed the fluctuation of the different waves, findings indicate that there is a strong positive correlation between alpha and beta-low waves in every tested condition. Particularly, the latter aspect advises that whenever an increase of the activity in one frequency occurs, a corresponding increase in the other frequency happens as a consequence. Regarding the comparison between gamma and alpha waves, there is an existing weak negative correlation, corresponding to an opposite behaviour from the previous case. Regarding "control-activity", the findings are substantially the same when comparing the different activities of the three analysed waves; In general gamma waves observed wider fluctuations with respect to the others the in real environment, and further analysis revealed that the experiment showed the control-activity stage being higher compared to the control-experience levels.

When comparing the brain activity of the second scenario, comprising electrical lighting, almost the same trend has been observed, despite the gamma curve in the "control-experience", as shown in the graph in Figure 19 , is overall below the alpha wave activity, except for two cases and present another variance as when alpha reaches two the highest peak, gamma showed to have the opposite trend. Regarding correlations, once again, alpha activity has proven to have a correlation with beta-low, which means there is a tendency for the activity of beta-low waves to increase according to alpha and the same inclination has been found for the second stage of performing the activity. Opposite, there is a contrasting tendency when analyzing alpha in regards to gamma: almost no relation in the first stage and a positive correlation in the second, while overall, the comparison revealed the control-activity stage being the dominant with the only exceptions of two participants who were more elicited in the control-experience stage in alpha and beta-low waves.

In addition, a similar analysis, comparing the same variables, has been carried out for the virtual environment. This allowed a thorough investigation of whether the virtual environment had a different effect on brain activity compared to the real environment.
As far as the correlation is concerned, when analyzing the "control experience" situation and comparing alpha-beta low values, a stronger positive correlation has been found and this is even higher if compared to the real environment; nevertheless, alpha and gamma waves resulted in a stronger and positive virtual environment, suggesting a higher level of activity and synchronization between these two waves. In the second stage, considering the "control-activity" situation, similar results have been obtained with the same confidence level for correlations and comprehensively the activity elicited the more intense activity of the three waves, except for just one case. Finally, with both the contribution of daylight and electrical lighting, the same inclination for both alpha to beta-low and alpha to gamma having the same degree and consistency in their correlation is found and the activity stage is reported to be the more evoking and stimulating for those waves.

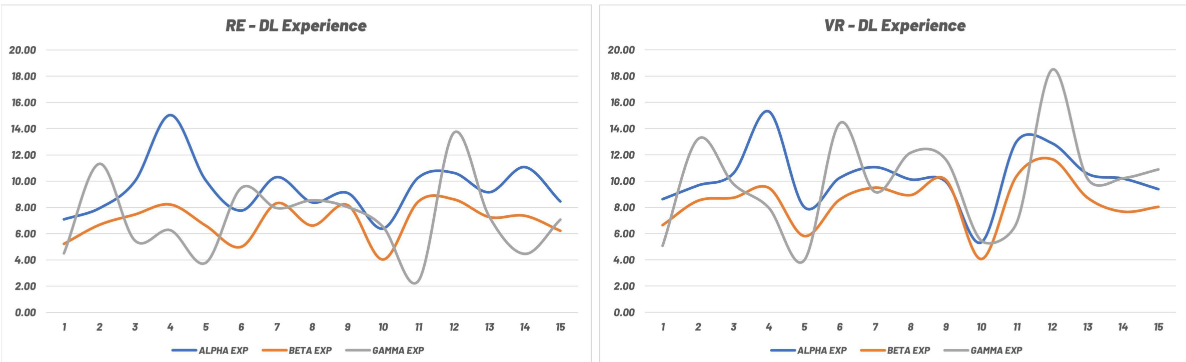

Figure 19. ***Left (a):*** Graph showing the various trend for alpha, beta-low and gamma waves in the RE, first scenario, and first stage corresponding to "control-experience", compared to the VR with the graph on the ***Right (b)***.

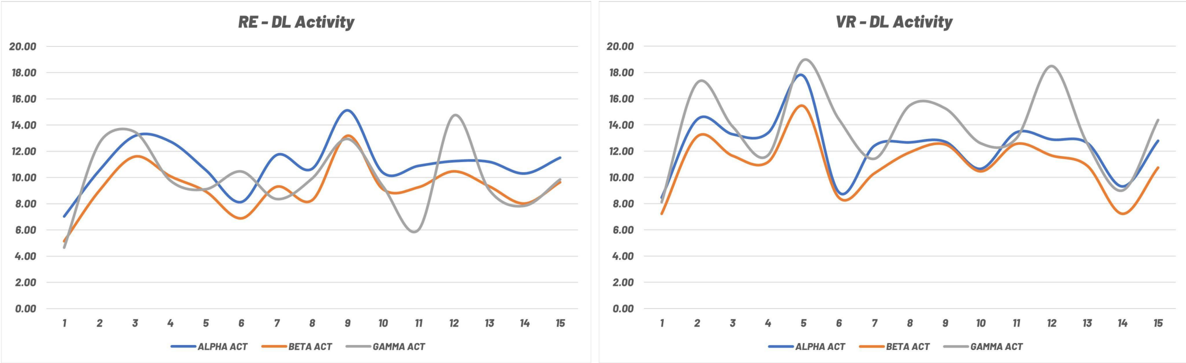

Figure 20. ***Left (a):*** Graph showing the various trend for alpha, beta-low and gamma waves in the RE, first scenario, and second stage corresponding to "control-activity", compared to the VR with the graph on the ***Right (b)***.

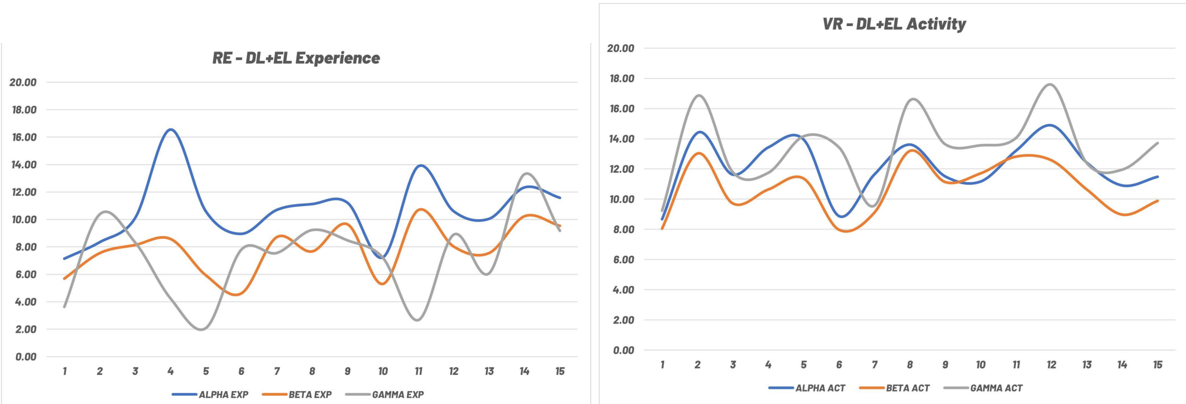

Figure 21. ***Left (a):*** Graph showing the various trend for alpha, beta-low and gamma waves in the RE, second scenario, and first stage corresponding to "control-experience", compared to the VR with the graph on the ***Right (b)***.

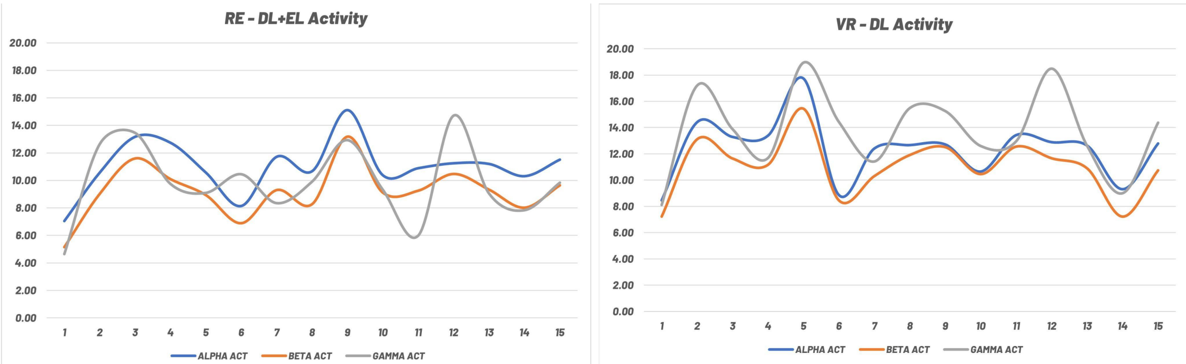

Figure 22. ***Left (a):*** Graph showing the various trend for alpha, beta-low and gamma waves in the RE, second scenario, and second stage corresponding to "control-activity", compared to the VR with the graph on the ***Right (b)***.

5.1.3 Correlation between mEDI and State of Emotions

The analysis proceeds to offer in the following chapter a further analysis between the melanopic equivalent daylight illuminance (mEDI) and the outcomes of the EEG recording as also shown in the next section (Paragraph 5.2.2) where the intrinsic and specific activity over of the selected waves and the increase or whether the decrease in such those to result in **valence** and **arousal**. Pearson and Spearman's correlation has been performed to seek to which extent those variables are connected and statistically meaningful; the EEG data, processed as shown in paragraph 5.2.1, were compared to the total mean average mEDI for all the participants. interesting findings regarding the correlation between the two environments could be deployed in regard to alpha, beta-low, and gamma waves and the subjective measures of valence and arousal. Based on the obtained results, in the real environment, considering the first scenario with the sole contribution of daylight, the Pearson correlation values between mEDI and the activities of the analysed waves were examined. Following in the table (XXX) all the results will be illustrated with a further explanation to follow.

Table 3. Table of the Pearson correlation (left) and Spearman (right) for each of the alpha, beta-low and gamma activities as measured over the experience/activity over the corresponding control phase.

Environment	*mEDI/*α **alpha**,		*mEDI/*β **beta low**		*mEDI/*ɣ **gamma**		*p test*
RE - DL (Experience)	0.25	0.20	0,02	-0,18	-0,02	-0,19	< 0.05
RE - DL (Activity)	0.30	0.26	-0,07	-0,07	-0,27	-0,38	< 0.05
RE - DL + EL (Experience)	0.07	-0.13	0,001	-0,46	-0,14	-0,03	< 0.05
RE - DL+EL (Activity)	0.31	0.37	-0,08	-0,03	-0,05	-0,13	< 0.05
VR - DL (Experience)	0.22	0.22	0,24	-0,23	0,24	-0,014	< 0.05
VR - DL (Activity)	0.09	0.20	0,21	0,30	0,21	0,56	< 0.05
VR - DL + EL (Experience)	0.45	0.26	0,40	0,23	-0,40	0,21	< 0.05
VR - DL+EL (Activity)	0.15	0.07	0,60	0,008	0,08	0,04	< 0.05

When analysing the Pearson and Spearman correlation between mEDI and alpha weighted results, a weak to positive Pearson correlation is observed in the RE whereas the Spearman points out a slightly weaker or even negative correlation. As far as the Virtual environment is concerned, the former values indicate a weak to moderate positive correlation and in the latter, slightly weaker.

Additionally, when analysing the correlation coefficient between mEDI and beta-low wave, activity was a very weak positive correlation if compared to the VR, where a weak to moderate positive correlation happened. Spearman correlation is even strongly negative (ranging from -0,46 to -0,07) where it fluctuates even more in the virtual world, ranging rom -0,23 to 0,3. Finally, the mEDI and the activity of gamma waves are explored, over the two stages and scenarios, and suggest a weak negative correlation for Pearson and an even slightly stronger negative for Spearman. Regarding the virtual environment, an opposite situation occurs as a weak positive correlation is found, while Spearman has the widest range of difference, ranging from -0.014 to 0.56, indicating a weak negative correlation to a moderate positive correlation. The above-reported findings indicate that there are still limited, and not balanced associations between mEDI and the activity of alpha, beta-low, and gamma waves. Although, with this being said, it must be stated that the shortcoming of strong correlations suggests that may be implicated other factors that are even fully explored in the present study and that possibly influence the mentioned relationship between mEDI and brainwave activity. Further research is warranted to explore additional factors and their potential influence on the observed correlations.

5.1.3 Analyzing mEDI and EEG Activity

To further explore the relationship between mEDI and EEG brain activity, a statistical analysis has been taken into examination to seek for any correlations between the melanopic EDI scores and the calculated valence and arousal ratings. After analyzing, both in the real environment and in the virtual world, in the first case with spectrometer measurements and in the other case, simulations with ALFA, it was possible to draw and establish an original and introductory approach for the neuroscience applied to lighting design. The ultimate purpose was to compare the effects of real and virtual environments on mental activity and what is more, and this was to be intended at creating a controlled environment that could be compared to a real environment.

5.2 Valence and Arousal

This section presents the results of two distinct analyses conducted after processing the various EEG data from each participant at different stages of the experiment, to gain a better understanding of the Arousal and Valence. The first analysis presented involves processed EEG data, followed by a brief explanation of the process to obtain such information to extract Arousal and Valence scores. As already mentioned before, those are important parameters, as EEG data is a direct measure of neural activity in the brain, to assess the affective states experienced by the participants during the study, both in the Real and the Virtual environment as well.

The second analysis will compare the Arousal and Valence scores obtained from the EEG data with those obtained from participants' subjective evaluation through the SAM (Self Assessment Manikin). This comparison enabled us to evaluate to what extent the level of accuracy of the EEG measures is when it comes to capturing the subjective experiences of Arousal and Valence reported by the participants, and to identify any discrepancies between the two measures. The comparison was of particular interest as it allowed us to explore whether the EEG gives an accurate reflection of the participants' internal states, and moreover, it could be used as a reliable tool for measuring affective states in future research.

By conducting these two analyses, the aim is to gain a more comprehensive understanding of the emotional experiences of the participants and to evaluate the validity of EEG measures in measuring subjective affective experiences. In the following sections, we present the results of each analysis in detail, highlighting the key findings and implications for our study. We then discuss the broader implications of these findings for the field of affective computing and future research in this area

5.2.1 *Processing data*

Each EEG recording was captured to be linked at only each specific stage, such as "control", "experience" and "perform the activity", by providing a snapshot of the limited moment. Subsequently, the results from the EEG were transferred, one participant after one another, saved and stored in Excel files. The Band Power EEG software automatically supplies data as samples per second; In this case, according to the literature research, only **α alpha**, **β beta low** and **ɣ gamma** waves and the focus was redirected already to the averaged values from the 8 channels. The number collects is equal to 25 samples per second, resulting in 750 rows for the "control" and 1500 for the "experience/activity". Next, the data processing will outline how the data was evaluated to present an overall understanding of valence and arousal.

1. As a first thing, in Excel a table was created divided by "first" and "second" scenarios, further divided into "control" and "experience/activity". Later each wave activity was inserted into the corresponding stimulus: for instance the 30-second activity for the control and the 60 seconds for the remainings.
   This procedure was then conducted for each stimulus and for each alpha, beta low and gamma. Resulting in 15 overall tables, containing RE and VR raw data for each participant.

   Table 4. Example of part of Participant 1 data reporting "Control" and "Activity" in the first scenario of the Real Environment Experiment.

Participant 1	*Control*	*Activity*
α alpha	7.6042	9.1032
β beta low	5.7069	8.5813
γ gamma	5.4045	10.2382

2. Next, the stimulus, corresponding to whether the "experience" or "activity" was divided by the corresponding control to understand the influence of each stimulus compared to the control. Following below is illustrated an example for Participant 1

   Table 5. Example of part of Participant 1 data reporting the division by the two controls and the corresponding "experience" and "activity" stimulus, in the first scenario of the Real Environment Experiment.

Participant 1	*Control/Experience*	*Control/Experience*
α alpha	0.8105	1.1971
β beta low	0.7777	1.5003
γ gamma	1.2633	1.8943

3. These above-reported values were then converted into percentages and then percentage change from control for ease of comparison. Importantly, the

percentage change accounted for the 'negative' change from control with the following formula, with point reference "control/Experience" value for alpha wave:

$$-100\%-81.0540\%=-18.94690\ \%$$

4. The above-mentioned process was conducted for all the participants, the scenarios and the two Environments that have been tested. Following the arousal valence was extracted for each participant. Notably, if the results are graphed, alpha or beta low are expected to be represented on the vertical axis, whereas gamma shows its scale on the horizontal axis.

A reduction in gamma waves is to be considered an increase in **valence**, while a reduction in alpha or beta low waves is linked to an increase in **arousal**.

5.2.2 EEG-derived Arousal and Valence

The results show a significant difference in valence and arousal ratings between the control/experience and control/activity stimuli in the Real Environment, even if compared between the scenario with the contribution of the sole daylight, to the one with electrical lighting. Participants were elicited more significantly with a higher increase in both positive valence and high arousal during the control/activity stimulus, with a no-significant sample that scored a decrease only in Arousal. As stated, the comparison between RE to VR shows the same behaviour in the "control/activity", where the highest correspondence for an increase in both valence and arousal is reported.
Specifically, the control/activity stimulus elicited a significant increase in both positive valence and high arousal, while the control/experience stimulus resulted in lower levels of both positive valence and arousal.

In the first scenario, the cross-validation of raw EEG data reported on average 79% correspondence when the increase/decrease of both valence and arousal was compared. Notably, in the Real environment, 7 participants reported a decrease in valence, whereas, in the virtual environment, only 3 reported a decrease, while those same also experienced the real environment. A slightly less percentage of participants recounted a decrease of both arousal and valence in respect of the Virtual Environment. Additionally, in the control/activity scenario, only one participant documented a decrease in arousal for alpha waves, whereas in the virtual environment, three participants reported a decrease in alpha waves and one of them also reported a decrease in gamma waves, indicating a decrease in valence.

Regarding the second scenario, which takes into consideration the contribution of electrical lighting, based on the EEG data collected, there was a 57% cross-validation score between the Real and Virtual environments, indicating an increase or decrease in valence and arousal. The standard deviation of this score was 33%, suggesting a wide range of individual responses. Data showed that 6 participants in the real environment reported a decrease in valence, meaning a reduction in gamma waves, compared to 5 in the virtual environment.

53% of the overall scores indicate a decrease in arousal, for participants experiencing the room in the Real environment as opposed to the same in the Virtual environment, scoring a 67%, whereas 46% indicated a decrease in arousal for beta low waves if compared to the 60% of the same participant in the Virtual Environment. Lastly, when it comes to evaluating the activity being performed in the virtual environment, results showed 3 participants reported a decrease in alpha waves in the real setting compared to 4 in the other one, which is a difference of 6.67%. The same difference appears when 2 participants are compared to only one for beta low waves and to conclude with only one participant documenting a decrease in valence in the virtual environment.

5.2.3 EEG Compared to SAM for Arousal and Valence Scores

To further explore the scoring for Valence and Arousal, the following proposed method is to compare EEG measures and results for alpha, beta low and gamma waves, to the Self-Assessment Manikin As, as a proof validation process between raw quantitative data and qualitative assessments. To do so, the results of the EEG data analysis to the self-assessment scores provided by the participants after each session when they answered the questionnaires. The scores, since were ranging on a Linekert scale of 1-5 were analyzed and the z score was normalized to visualize the plot scattering graph. to determine the level of agreement between the two methods of measuring valence and arousal. In addition, we explored the discrepancies between the two methods and discussed possible explanations for the differences observed.

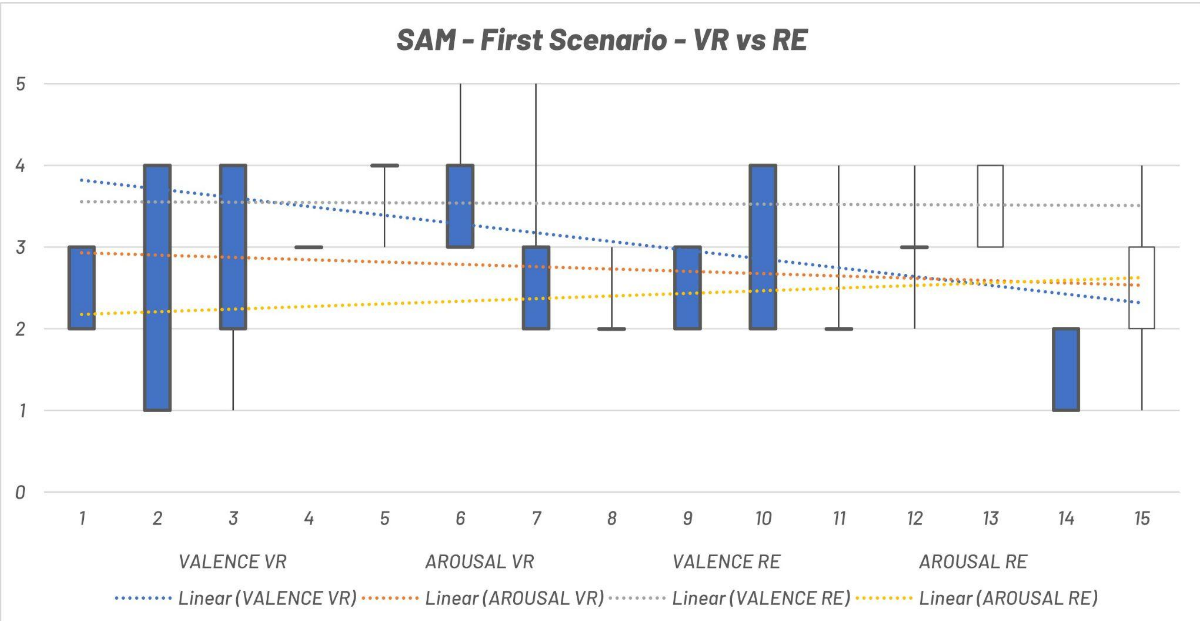

Figure 23. Distribution graph of the comparison of the Self-assessment Manikin questionnaire. Valence and Arousal are being compared based on the participant scoring for the first scene between the VR and RE. On the vertical (Y) axis the Linekert scale from 1-5 is displayed and on the horizontal (X) axis, the number of participants. The Linear regression is also shown for each of the variables

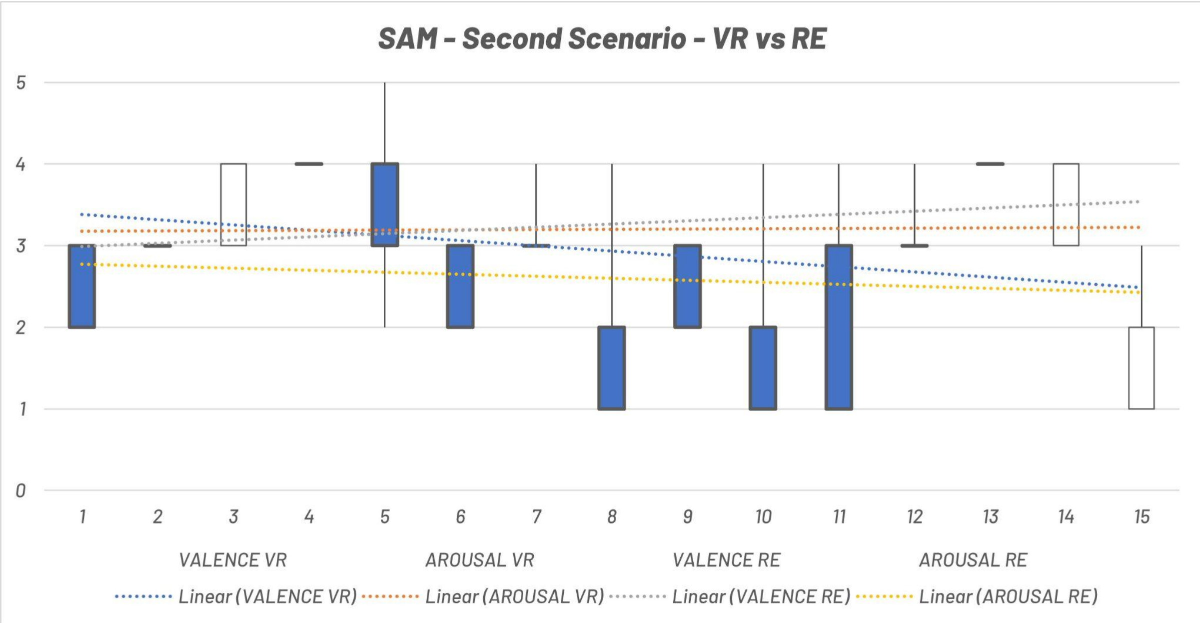

Figure 24. Distribution graph of the comparison of the Self-assessment Manikin questionnaire. Valence and Arousal are being compared based on the participant scoring for the second scenario between the VR and RE. Linear regression is also shown for each of the variable

Subsequently, as the statistical significance rated $p<0.005$, the results were plotted in a formula to match the strict correspondence between EEG and SAM questionnaire: if the percentage changes in alpha, beta low and gamma waves were crashing, reporting an increase in both valence and arousal and the scored outcomes from participant rated ≥3, which was considered as a neutral state, then there was a "MATCH" between the self-reported valence and arousal and the respective EEG expressed in percentage changes.

In regards to the Real Environment, during the first scenario and considering the "experience" as opposed to the "control", only 20% matched between EEG-measured arousal and self-assessment manikin scores while 47% matched for the valence; in contrast, for the control/activity scenario, 5 out of 15 participants (33%) had matching scores for arousal and 13 out of 15 participants (87%) scored a match for valence. During the second scenario, which included the contribution of electrical lighting, there were 4 out of 15 matches (27%) for arousal and 7 out of 15 matches (47%) for valence when analyzing the experience of the room, while there were 7 out of 15 matches (47%) for the arousal and 13 out of 15 matches (87%) when performing the activity. These results suggest that there were higher levels of agreement between the EEG measures and self-assessment manikin scores when performing the practical activity when it comes to valence.

To further continue the exploration of the validity of EEG measures and compare them to the self-assessment scores provided by the participants, the analysis of Virtual Reality follows along. The obtained results in the first scenario, considering only the sole contribution of daylight, reported 4 out of 15 participants having a match for the increase or decrease in arousal between their subjective self-assessment of arousal and the EEG-recorded changes in arousal (26.7%), while 10 out of 15 showed a match for the trend in valence (66.7%).

In the same scenario, when evaluating the performance of the activity with controllers, 9 out of 10 participants (90%) had a matching rate in regard to arousal, while 10 out of 15 participants (67%) had a match for valence. Lastly, In the second scenario involving both electrical lighting and daylight, only 2 out of 15 participants exhibited a match between their subjective self-assessment of arousal and the recorded changes in arousal captured by EEG (13.3%), while 8 out of 15 showed a match for valence (53.3%). Moreover, when the participants performed the activity in the same environment, 7 out of 15 participants showed a match between their subjective self-assessment of arousal and the EEG-recorded changes in arousal (46.7%), while 11 out of 15 showed a match for valence (73.3%).

Interestingly, when comparing the control/Experience scenario with the control/Activity scenario in terms of valence and arousal changes, there was a significant difference in the number of participants who reported an increase in emotional response. In the control/Activity scenario, both valence and arousal showed an increase for most participants, while in the control/Experience scenario, only a few participants reported an increase in valence and arousal. These results suggest that the virtual environment in the second scenario may have elicited a more consistent emotional response compared to the control scenarios.
These findings suggest that engagement in physical activity may enhance positive emotional experiences and that such effects are not solely dependent on the context of the experience. This has important implications for the promotion of physical activity as a means of enhancing emotional well-being".

5.3 Perceived Presence and Level of Realism

5.3.1 Performance of practical activity

Each participant completed a practical task, both in the Real Environment and in the Virtual one as well, consisting of disposing of a series of nine squares, numbered from 1-9, in ascending or descending order. No instructions nor directions about the rapidity were asked in order to accomplish the task, as they were just judged for their total completion only based on the available time. A table that summarizes the time for the completion for all the participants is presented below in Table 6.

The activity performed in the Virtual reality was limited as the participant received rapid and essential training prior to the test when compared to the real-world performance.
From the table, it could be assumed that participants performed quicker in the first scenario, with daylighting, if compared to the second scenario; on the other hand, given the limitation in the virtual environment, the sample for the testing employed more time than the real setting activity, and sometimes, specifically in three cases, the performance had been declared not completed due to an excess in the given time.

Table 6. Chart showing, for each participant, the completion time for performing the activity in both the RE and VR and in the first and second scenarios.

N° of Participant	*RE First Scenario*	*RE Second Scenario*	*VR First Scenario*	*VR Second Scenario*
#1	23 sec	24 sec	41 sec	52 sec
#2	12 sec	16 sec	47 sec	55 sec
#3	13 sec	17 sec	47 sec	54 sec
#4	26 sec	29 sec	48 sec	33 sec
#5	24 sec	29 sec	46 sec	32 sec
#6	24 sec	26 sec	40 sec	40 sec
#7	21 sec	20 sec	58 sec	NOT COMPLETED
#8	25 sec	23 sec	37 sec	58 sec
#9	23 sec	23 sec	35 sec	30 sec
#10	15 sec	20 sec	50 sec	38 sec
#11	23 sec	27 sec	42 sec	35 sec
#12	25 sec	17 sec	47 sec	36 sec
#13	28 sec	28 sec	44 sec	NOT COMPLETED
#14	23 sec	15 sec	NOT COMPLETED	52 sec
#15	22 sec	17 sec	55 sec	51 sec

5.3.2 Comparison between RE and VR

For each of the environments, Real and Virtual, a set of questions highlighting attributes and qualities have been asked to each participant who eventually evaluated after having been exposed to each stage to accurately measure their experience and perceived realism. Based on the answers and results obtained by analyzing the questionnaires could be assessed.

From the graphs, we can see that VR and RE are generally similar and separate people's answers to a max of **40%-60%** and the closest to **47%-53%**.
When estimating if the sample of the tested population performed that light was enough to perform the activities that were needed to perform. Notably, on average they scored **4,6** of preference for performing the activity in the first scenario, whereas **4,9** in the second scenario. Regarding the preference linked to the various scenarios where performing the activity task, **53.3%** of the sample (=8 individuals) reported the first scenario, connected to the sole daylight situation, as the most favourite for better performing the task. As far as the VR world is concerned, a mean score of **4.4** and **±0.8** thought the light intensity was enough to achieve the

activity in respect of the **4.7** with a standard deviation error of **±0.6** with a preference for the second scenario with electrical lighting.

In the Real-world, 60% of the sample (=9 individuals) reported the first scenario, connected to the sole daylight situation, as the favourite for better illuminating the space, compared to only one participant in the Virtual experiment. Lastly, as the inclination to switch and move the objects during the activity, a little discrepancy has been observed as the first scenario ranked as the more chosen against only six participants who performed better in.
The largest portion of people surveyed (**47%**) reported being extremely satisfied with how well virtual reality represented the real environment, while another **33**% expressed overall satisfaction. These results are particularly noteworthy since the goal was to make the virtual reality experience as similar to the physical environment as possible, in order to obtain more precise data from the EEG helmet.

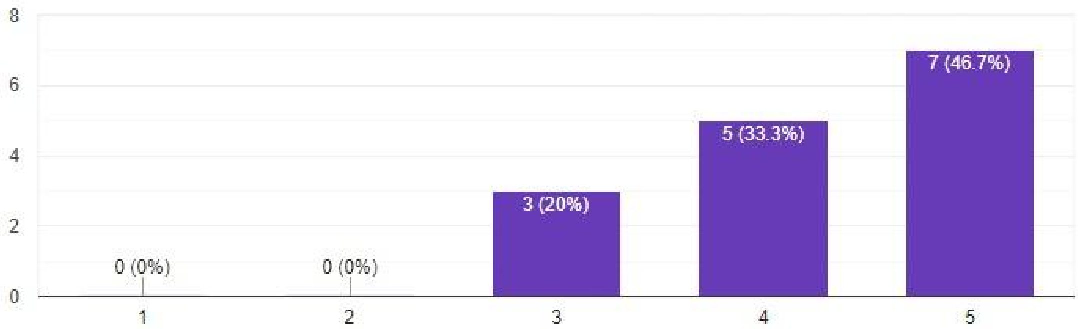

Figure 25. Graph of the outcomes from the questionnaire. Participants rated their level of satisfaction for a proper representation of the VR in regards of the RE

According to our research findings, a majority of almost **60%** of participants reported high levels of satisfaction with the realism of the virtual reality environment, while the remaining **20%** expressed a moderate to low level of satisfaction. While the consistency between the virtual environment and physical environment was rated as neutral or satisfactory by **40%** of the participants, the main area of concern was the lack of realism in the virtual environment due to the absence of HDRI pictures in the Unreal Engine.

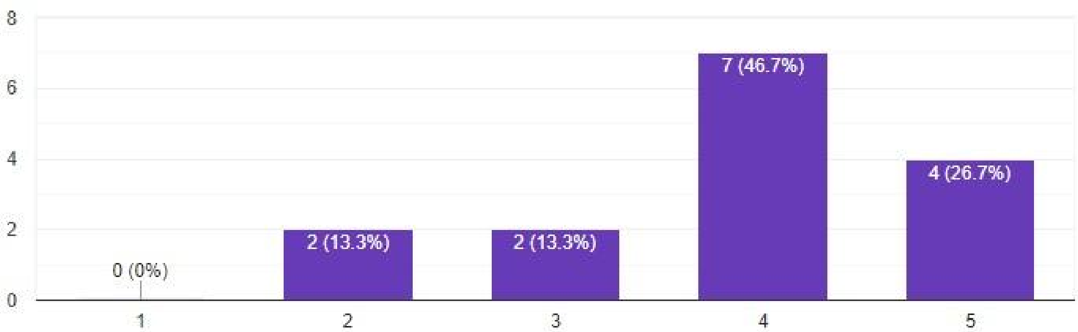

Figure 26. Graph reporting the results from the questionnaire. Participants answered if they noticed any differences in the lighting both in the VR in regards to the RE

It is worth noting that we were not able to include HDRI pictures due to time constraints during this phase of the project. By incorporating HDRI pictures, we aim to improve the level of immersion and engagement in the virtual reality experience and provide the users with a more realistic experience.
In summary, while a majority of participants were satisfied with the realism of the virtual reality environment, there is significant scope for improvement in terms of consistency and overall realism. Additionally, the study found that a significant majority of participants, 60%, reported a more enjoyable and easier experience to put black square numbers in a row using their hands to put them in a row, compared to using the VR interface. This finding is not surprising given that VR controls can be more challenging to navigate and require more physical movement than traditional hand movements.

During the course of the project, participants were required to wear an EEG helmet and a VR helmet while sitting in a spinning chair for a total of 30 minutes. Understandably, by the end of the session, many participants reported feelings of fatigue and visual exhaustion.
However, despite these challenges, a final report showed that fatigue and visual exhaustion did not appear to have a significant impact on the quality or accuracy of the obtained data from the EEG helmet. While the physical discomfort experienced by some participants was understandable, it did not detract from the validity or reliability of the data collected through the EEG helmet. These findings further underscore the utility of EEG technology in measuring brain activity during VR experiences, even under conditions of physical discomfort or fatigue.
Although other graphs showed us that people were satisfied with the level of detail that was achieved in virtual reality, 40% and the quality of materials 33% were satisfied with it.

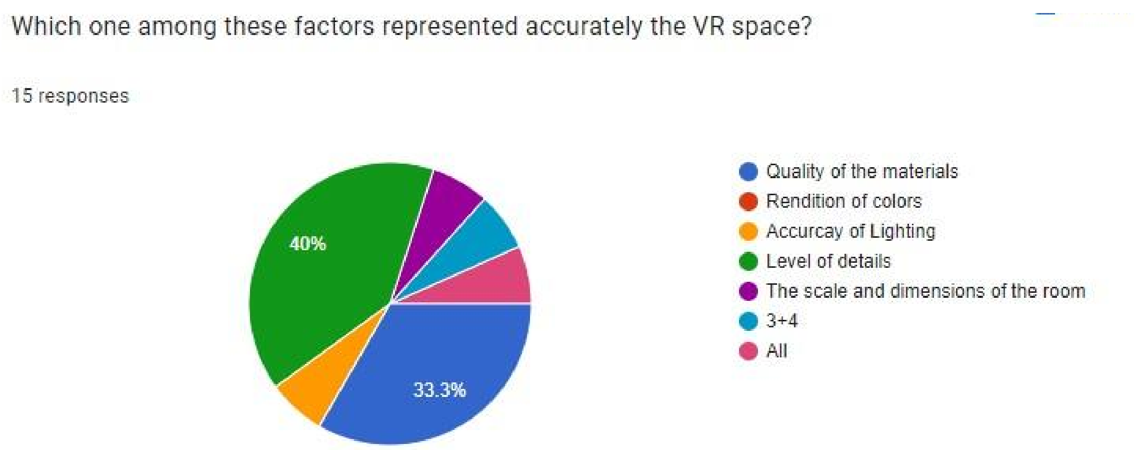

Figure 27. Pie chart showing the different outcomes from the questionnaire to the question on among factors and the ability to accurately represent the VR space.

However, the graph also reveals that a portion of the participants (26%) reported dissatisfaction with the realism of the virtual reality experience, particularly with regard to the level of detail. Additionally, the study found that although the quality of the materials used in the virtual environment was high, some participants (20%) felt that the rendering of colours on these materials was inaccurate.

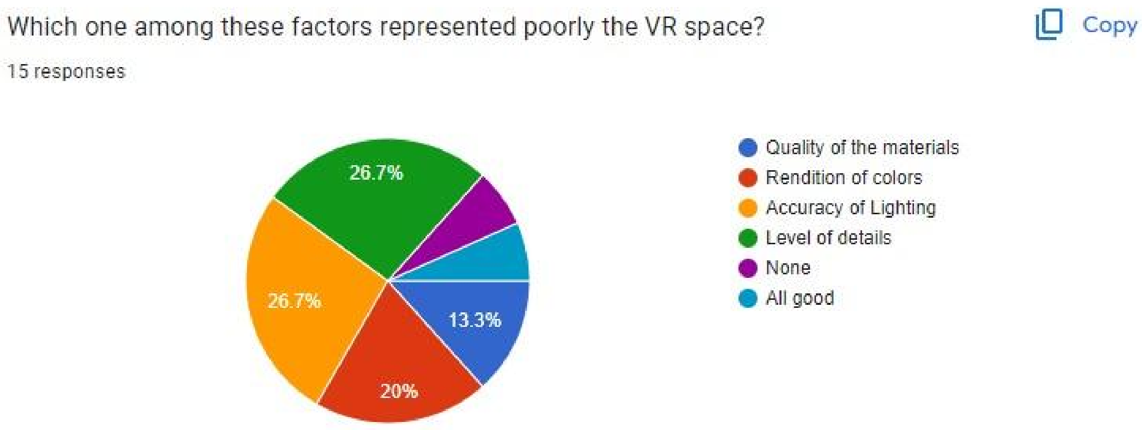

Figure 28. Pie chart showing the different outcomes from the questionnaire to the question on among factors and the low ability to accurately represent the VR space.

Furthermore, some comments have been received from open questions from the participants regarding specific further observations: for instance, when the room was receiving warm light and the sun was at its highest peak and were getting the really harsh shadows and strong lights. In this situation, the whole brightness of the room was increasing a lot considerably in its white colour, whereas in virtual reality the entire appearance was getting to an unrealistic situation with a glary perception. One of the factors that does that must be the bad rendering of the colours and more work is needed to the material work possible.

6 Discussion

In the next section an analysis of the outcomes and results from the experiment will be provided, comparing them with other relevant studies, when possible, to finally highlight further limitations and possible issues occurring from the test will be argued.The experiment has been conducted across a period of five days and involved fifteen participants, to seek the possible answer about the connection between the melanopic response and the state of the emotional activation; therefore, as a field experiment as to be considered original in its purpose and may serve as a shred of evidence for further studies, with perhaps more variables, a larger sample of participants and equipment, to possibly confirm or offer other results. An examination has been carried out including the effects of exposure to light, daylight and electrical lighting in an office environment, both in the real setting and in an immersive computer-generated virtual space, that recreated the same premises of the former.

On one hand, measuring melanopic EDI has been measured to seek the possible impact on the brain activity of each individual and moreover to find correlations between the non-visual effects of lighting and the state of the emotions. The fluctuations in the curve of the melanopic equivalent daylight illuminance were analyzed in both the real setting and in the virtual one and demonstrated to have consistent and significant differences, where the tendency across the period of the test remained overall above the recommended 250 mEDI at the eye level, except when participants were tested late in the night or during overcast and cloud days. What is more, the addition of electrical lighting raised the income of the mEDI as expected and did the same in ALFA software. In regards to the circadian rhythm simulation tool it must be stated that despite the program offering freedom to adjust multiple parameters to match the real setting conditions to propose a valuable comparison, a brief comparison reported a discrepancy in the whole income of proper activation of the circadian rhythm; ALFA in most of the case across the experiment period, underestimated the total mEDI provision that was calculated by the spectrometer in the real world environment and has to be considered as the most accurate mean to have an understanding. A thorough analysis and cross-validation of the different data between the two environments has not been performed and therefore the level of accuracy and reliability of the result has to be considered moderately significant with sometimes a higher extent of unpredictability. When it comes to matching unfavourable conditions the gap tends to reduce as the software is able to offer stable and reliable results, whereas on other conditions ALFA could not take into consideration real-world conditions and variations such as strong reflections and glare.

The study outcomes unveiled some important and remarkable observations regarding the EEG data which were collected during the experiment, both in the real environment and the virtual one. The different wave activity accounted in the alpha, beta-low and gamma, were considered for two different stages in two different scenarios.

In the "control-experience" and the "control-activity", for all the lighting scenarios and in the two stages, a strong positive correlation between alpha and beta-low waves was highlighted, revealing that an increase in activity in one frequency is accompanied by a corresponding increase in the second one. However, the correlation between alpha and gamma waves exhibited contrasting tendencies between the first and second stages, reporting a weak negative correlation between alpha and gamma, with unpredictable and rapid variation in the

interaction between each other. Overall, the control-activity stage caused higher activity levels compared to the control-experience stage, except for two participants who showed the opposite. The investigation was also directed at the virtual unfavourable, allowing for a comparison of the effects on brain activity between the environments. Once again a stronger positive correlation between alpha and beta-low waves was found slightly higher in its consistency if compared to the real setting. In contrast, a different relation was noticed when comparing alpha to gamma waves, which showed a stronger and positive correlation in the virtual environment, which was followed by a similar level of consistency in the "control-activity" stage. To recapitulate, promising and evident results have been provided in this study, suggesting a possible impact caused by activities or different lighting conditions; but most importantly, the immersion in a VR environment proved to have higher levels of activity and synchronization between alpha and gamma waves, especially when analyzing the activation during the performance of an activity. Lastly, the investigation aimed to deploy the relationship between the melanopic equivalent daylight illuminance (mEDI) and the processed EEG recordings with the assumed waves and their implication of valence and arousal, by performing simple correlations. The results highlighted interesting but contrasting correlations between mEDI and brainwave activity in both the real and virtual environments: in the real-world setting, weak to moderate positive correlations were obtained by the two correlation factors, as also noted in the virtual environment, especially if alpha waves are compared with mEDI. Beta-low waves had contrasting results from the previous case, which were accounted for even more negatively by Spearman, suggesting a great level of variability in the relationship, where finally the correlation with gamma waves displayed the same result if not slightly negatively stronger.
What it stands out to be very interesting concerning the virtual environment is the different pattern that was analysed, with a weak positive correlation between mEDI and gamma waves according to the Pearson correlation, whereas the Spearman correlation, scored a wider range of differences.

The present study also investigated to what extent the state of the emotion is elicited while being exposed to certain lighting conditions in two different environments and therefore two features could be emphasized such as that using a VR headset to immerse participants could also affect his/her valence and arousal as much as a real-world environment could do. Moreover, performing a practical activity to be performed in both of the real and virtual context, proved to have the same level of activation for the state of the emotion, although, under specific lighting conditions is not fully clear how this could affect the virtual environment.
Many variables must be taken into account, for instance, Castilla et al.[1] who reproduced three different illuminance levels to ensure that these levels were as much close to reality; consequently, this could be a future approach and suggestion to the present study, to include accurate lighting patterns that could affect the cognitive performance or the experience, to create more responses.

What is more the current study demonstrated that the thin line that could divide the real and the virtual world, is soon to be filled as the psychological responses are comparable since VR can be used to analyse individual's cognitive performances, as the experiment is performed, and evaluating them in different lighting scenarios. To the author's best auspice, the following research could be of great help to understanding these dynamics to further improve the lighting design of new real-world environments.

Overall the results, when measuring and evaluating valence and arousal showed some interesting patterns along the lighting conditions and stage, where the activity performance scored the highest results for both of them, while the electrical lighting along with daylight scored a slightly negative outcomes if compared to the first scenario. On the other hand, VR had a lower accuracy to match the real world only in the case of the "control experience" with electrical lighting, though being very encouraging for the rest of the outcomes. It must be stated that all results were compared to the control stage, which has to be considered as a static, adaptive and preparatory phase. Therefore, even though some results appear 'negative' only in relation to the control state. The cross-validation between raw processed EEG signals with the activity of valence and arousal aligns with the self-assessment given by the questionnaires, which is again particularly significant as there might be a gap between subjective and objective ratings. encouraging. To provide more solid and valuable outcomes, the different results from each wave could be plotted on Russel's graph to further evaluate high/low valence and arousal.

Finally, significant similarities and differences were revealed between the real and virtual environments in terms of participants' experiences and perceptions. The questionnaires highlighted that VR and RE were generally similar, with the rating of participants' choices, varying and differing. Reported light intensity in both scenarios, was generally sufficient to perform the activities required, with a slightly higher preference for the second scenario in both environments. In the real environment, the first scenario (sole daylight) was the most favoured; In terms of switching and moving objects during the activity, the first scenario was more commonly chosen in both environments. The majority of participants expressed satisfaction with the realism and the accuracy of the virtual reality environment, which align with Chamilothori et al.[10] and the positive results regarding the perceptual accuracy of the VR method. Although some of them reported a level of dissatisfaction with realism, specifically mentioning issues with the rendering of colours and unrealistic perception of light and shadows. Further work is needed to improve colour rendering and material representation in the virtual environment However, there are certainly ways to improve, both in terms of consistency and overall realism, where for instance, the lack of HDRI pictures in the Unreal Engine was identified as a factor affecting realism of the virtual environment.

7 Conclusion

Overall, this thesis aimed to explore and discover the possible relation between how much our circadian rhythm gets affected by various lighting conditions, by monitoring an individual's mental activity with an EEG helmet, while measuring the melanopic response. Furthermore, when processing the raw data from the EEG channels combined together and assuming some of the major waves, how those can elicit the state of the emotions, specifically valence and arousal. The methods presented in this research study through its experiment, only focused on two lighting scenarios, such as daylight and electrical lighting, where the latter has been considered only with fixed conditions and qualities.
The circadian rhythm can influence emotional experiences and its regulation is affected by various factors that sometimes could lead to an impairment of the emotional regulation. The main interest of the present study is to address the potential role of circadian rhythms in modulating emotional experiences and regulation; with this being said, the research questions have been formulated so that the process could lead to testing it, throughout the present thesis:

- *"How can a Neurophysiological approach unveil the pattern of the circadian influence in both real and Virtual environments?"*
- *"How can a Virtual Reality approach, could mimic a real-world situation and offer a level of Realism such that it could evoke positive emotions?"*

In order to answer these questions, a pilot test was conceived to seek for the good premises of the initial hypothesis and thereafter a field experiment was carried out, testing the real and the virtual environments, with two different activities under two lighting scenarios. The existing lighting and the available dynamics of daylight were deployed during the experiment and the track of the same conditions were applied in the virtual environment. However, accounting for the impact on the circadian rhythm was not feasible in the context of ALFA due to the intrinsic characteristics of VR headsets. VR headsets emit blue light wavelengths that may not be accurately measured, representing a different situation from the actual impact of circadian rhythms on the body. Therefore, investigating the circadian rhythm, as filtered by VR headsets was not the primary focus of this study Though, this present study was only focusing on comparing the effects of real and virtual environments on brainwave activity, and the use of the VR headset was intended to create a controlled environment that could be compared to a real environment. A mixed method of quantitative EEG raw and processed data, tested the brain activity by means of the reading of three different waves, and qualitative questionnaires with ratings, sought to seek validation with the obtained data and also to achieve a deep understanding of the the level of realism and perceived presence in between the two environments. The test which has been conducted with a reasonable sample of participants, and thereafter the analysis of all the variables indicated that different lighting conditions elicit a different state of emotions as well as different activities performed with the same variables, have a precise impact. Without any doubt, a more in-depth analysis and research are needed for the data outcome of this experiment, to possibly offer further explanations.

Furthermore, this study, despite its earlier nature as an innovative approach, is considered to have significant implications for understanding the role of lighting in promoting circadian health and emotional well-being. There is certainly a potential link between brainwave patterns and emotional states. Further research is needed to explore the underlying mechanisms and validate these findings in larger and more diverse populations
Implementations and optimizations of the light environments could be suggested in the real-world setting to inform lighting design in a variety of applications, such as hospitals, schools, and workplaces.

8 Limitations and Future Works

Overall, one of the main limitations of our study, concerning the accuracy and the close level of realism of the virtual environment, when using Unreal Engine, was that it did not fully mimic the visual field of the outside view that was aimed to replicate the real environment. Participants reported from the outcomes of the questionnaires that factors such as "accuracy of lighting" and "level of details" poorly represented the VR experience; the recreated DDL model, when set up on Unreal Engine, was missing a real sky condition as double dynamic presets skies were used. As a result, a white, overexposed window with a visible grey line on the ground was displayed, reducing the overall realism of the virtual environment. This limitation may have negatively influenced the level of virtual participation and immersion that was experienced by the participants. In the future, there is the aim to address this limitation, by providing and incorporating a more accurate representation of the whole environment with a High Dynamic Range Imaging (HDRI) image that replicates the view from outside the building and could provide a more accurate representation of the lighting conditions. The advantages would be loads and will eventually bring greater realism, with accurate lighting, reflections and most importantly consistency with real-world lighting.

Further improvements to the integration for a quicker workflow could be implemented in the way Unreal Engine receives the 3D model, without necessarily passing by Twinmotion to apply materials. As only one participant reported "a bit of headache and trouble to focus eyes"; this could be solved to maximize and increase the FOV (field of view) which in this experiment, the Oculus Quest had an 89° FOV. This will enhance the virtual reality perception, both for not being eye constrained in a limited field of view and as explained by Chamilothori et al.[11] by providing a wider field of view with better quality, there would be a better experience in the virtual perception assessment.
Regarding ALFA, even though it seems a promising tool for measuring the non-visual effects of light on individuals, it still lacks accurate calculations if the purpose is to mimic or validate real-world results. However, cross-validating the result was not the intention of the present research study. Furthermore, one must take into consideration that the program does not take into account individual differences in circadian rhythms, as it does not allow any defined spectral daylight data, and this is certainly a limitation when addressing that. In the future, it is suggested, despite it would require more advancements in the available technology, to dispose of a little spectrometer sensor inside the VR headset to measure the light spectrum emitted by the headset with the purpose to provide a more accurate evaluation of the impact of VR on the circadian rhythm, although, it is important to consider ways to control the effect of blue light

when using VR headsets or explore potential differences between headsets with and without blue light filtering.

The Self-Assessment Manikin (SAM) was only presented to participants after each scenario, rather than after each individual activity within the scenario that included four for each environment. This means that participants were only asked to evaluate their valence and arousal four times instead of eight times, which could have limited the integrity of the comparison between the EEG data and the SAM scores.

One potential way to address this limitation would be to modify the experimental design to include SAM ratings after each individual activity within the scenarios, rather than after the entire scenario. This would allow for a more extensive similarity between the EEG data and the SAM scores and could provide more insight into how participants' valence and arousal fluctuate throughout the different activities.

Regarding the suggested ways to address future research applied to Neuroscience and the use of EEG for lighting design evaluation could be conducted to investigate the appropriate amount of time of exposure for participants, or whether the sensitivity of EEG and their wider or smaller impact on individual's mood. Lastly, further indications are addressed and aimed to deploy more knowledge of the different band waves and their possible implications on the state of the emotions.

With this being said and all the findings being presented, a deep knowledge of these correlations can lead to the advancement of lighting approaches that can support circadian rhythm and well-being, while at the same time, providing valuable insights into how lighting design can contribute to creating supportive environments that can elicit the state of the emotions. It is important to interpret these results cautiously and consider additional factors fully not yet explored in this study that may influence this relationship. Further research is needed to investigate these additional factors and their potential influence on the observed correlations.

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