



**COGNITIVE EFFECTS OF SHORT DURATION SHORT WAVELENGTH
VISIBLE LIGHT**

THESIS

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AFIT-ENG-MS-18-M-012

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LIGHT

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Abstract

Light plays a critical role in the human experience. Not only does it provide a way for humans to view the world around them, but it also aids in the synthesis of vitamin D, is a treatment option for depression, and aids in alertness. However, until the last few decades relatively few studies specifically focused on the non-visual effects of light, and only recently have organizations begun looking at alertness, sleep pressure and other non-visual effects of light which are likely to impact worker productivity. This thesis research examines the effect of short duration, high intensity, short wavelength light with the goal of determining if converting typically white colored lights in breakrooms and bathrooms to blue will cause workers who normally work in a low light environment to be more alert and productive.

Sixteen participants were outfitted with Electroencephalography (and Electrooculography (EOG) equipment before being exposed to 200 lux of either 460 nm blue light or D6500 white light for 30 minutes. Afterwards, the light levels were changed to 3.5 lux of D6500 light and the participants were asked to perform six cognitive tests that were selected to measure response time, response control, selective attention, working memory and semantic memory. Results showed that the white light condition improved response time over blue light in tasks that required a choice to be made (not all analysis techniques showed statistical significance), but had no effect on accuracy. Similarly, subjective alertness as measured from the Stanford Sleepiness Scale showed a

lower decrement in alertness over time in the white condition over the blue condition, but initial alertness was less affected.

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COGNITIVE EFFECTS OF SHORT DURATION SHORT WAVELENGTH VISIBLE LIGHT

I. Introduction

Up until the 1980's only a few studies had focused on the non-visual effects that light has on the brain [1]. It was apparent that there was a correlation between light and how it affected brain processes such as circadian rhythm, alertness and response time, but no one was certain how the effect was created. However, it was apparent that the effect was not processed in the same manner as the visual effects of light (human sight) since some blind individuals were found to be affected by light as well [2]. In the 1990's an explanation was postulated. In 2002, a new photoreceptor cell was found in the eye and named the intrinsic photosensitive retinal ganglion cells (ipRGCs). The cells were found to play a role in the non-visual effects of light and were most sensitive to short wavelength light. This discovery increased the research focus in non-visual lighting effects.

Exposure to natural daylight had always been the primary method of light exposure, including blue light, necessary for circadian rhythm photoentrainment. However, the advent of technology has created a new means of blue light exposure in the form of an electronic display. In fact, these electronic displays have become so ubiquitous that their use has prompted a number of studies on the increase in blue light exposure. Some of these cognitive effects have been shown to be beneficial to humans, but others are a bit less desirable. All wavelengths of light have been shown to increase alertness, help memory and improve mood, but there are areas in which blue light has been shown to impart a greater effect. As an example, blue light tends to improve

response time more than green or amber light [1], [3], [4]. Blue light can lead to a number of negative effects, including circadian rhythm disruptions and the suppression of evening melatonin production [5]–[8]. Investigating the effects of blue light will provide a means to use it safely and effectively in the workplace.

Most previous studies on blue light have examined the effects of long duration (an hour or more) exposure to blue ambient lighting at night while completing a task. These studies chose to do the studies at night when melatonin levels were high because it was theorized that light improved alertness by suppressing melatonin production. More recently, researchers have begun to focus on the daytime effects of blue light when melatonin production is already low. They have found that blue light still is able to increase alertness and provide beneficial cognitive effects without the suppression of melatonin. Products are now being developed that provide direct blue light exposure for short periods of time (up to 30 minutes) at the beginning of the day. They claim to improve cognitive abilities and regulate circadian rhythm. If true, this could be an incredibly important tool for individuals who are required to work in dim lighting conditions. However, this area of lighting studies is sparsely researched and has plenty of conflicting information. Before thousands of dollars are spent converting lights to work in unison with biological processes, it is important to determine if the cognitive improvements are consistent and worth the cost.

1.1. Organizational Focus

Intelligence analysts perform a number of jobs to gather information to inform decision making and maintain the safety of the nation's people. Fulfilling one of those jobs, the imagery analyst looks at images such as satellite or overhead aerial photos to

gather information on enemies or to determine the current state of a particular location. Often, the objects in these images are purposefully concealed and thus appear similar to the image background, making them difficult to detect. Low ambient lighting is used in these workspaces because bright ambient lighting within the image analyst's environment would reflect off of the analyst's image displays. This would increase glare and decrease object contrast which further would further reduce the analyst's ability to detect the objects. Even with the newer and more advanced displays, the need for reduced ambient lighting is evident. Conversely, it is well known that working in low lighting environments causes a decrease in alertness [2]. This loss in alertness is exacerbated by shift work which results in circadian rhythm disruptions, and long work days which result in fatigue. However, it has been deemed more important for an individual to be able to identify the objects in an image than to increase operator alertness. Therefore, the ambient lighting in analyst workspaces is reduced significantly. Unfortunately, since imagery analysts and other intelligence operators work in combined workspaces, everyone is subjected to the same dim lighting conditions whether they enhance or degrade their performance and these conditions have become accepted when working in the intelligence field.

One particular unit that is affected by this issue is the 480th Intelligence, Surveillance and Reconnaissance (ISR) Wing where the intelligence operators have worked under dim ambient lighting conditions with constantly changing shifts consistently over the last few decades. To address the decrease in productivity, an idea was brought forth by the wing to place blue light in breakrooms and other common areas within their units. If the ambient light cannot be increased in work centers, it is hoped that

short exposure to intense blue light prior while outside the low light environment can be used to elevate alertness when operators are needed to return to the low light conditions. However, while the effect of blue light is known, it is not readily apparent if pre-exposure to blue light will create a significant enough effect to effectively improve worker performance. This research aims to provide data that will help leaders of those units make a decision about lighting conditions in areas outside the low light environment.

To determine if blue light is effective, there are various ways to measure a person's alertness. While somewhat subjective, the easiest way to evaluate alertness is to simply ask someone how alert they feel. Various scales have been created to help quantify the "feeling" of alertness or fatigue such as the Stanford Sleepiness Scale (SSS) [9] which asks participants to rate their level of fatigue on a scale from 1 to 7. Additionally, cognitive tests such as Reaction Time Tasks (RTT) and working memory tasks provide insight into the ability to use various brain functions. Electroencephalography (EEG) has been known to show a reduction in activity in the alpha and theta frequencies (4-12 Hz) upon becoming more awake [10]. Additionally, alertness is marked by the reduction of slow eye movements and increase in the number of eye blinks [10]. Electrooculography (EOG) can be used to measure this phenomenon. Using these measures and potentially some machine learning techniques should help to understand the correlation between blue light and cognitive performance.

1.2. Research Questions

The research outlined in this paper focuses on the non-visual daytime effects of pre-exposure to blue or white light prior to being placed in a dark working environment.

Since light can impart various non-visual effects, the following questions will focus the goals of this research.

Q1. Does exposure to 30 minutes of short-wavelength light prior to a task improve cognitive performance over full spectrum light?

The experiment designed for this research incorporated a treatment of 30 minutes of short-wavelength or full spectrum light prior to the performance of various cognitive tasks in a low light environment. Additionally, participants were fitted with EEG and EOG devices to measure their physical responses during both the pre-exposure and the low light condition to help in future analysis of the data. Analysis of the performance on these cognitive tasks recorded after each of the two pre-exposure treatments will help to determine if cognitive performance was improved.

Q2. Do demographics such as eye color or other external factors play a role in the effect of light exposure?

Prior to the experiment, participants were asked to answer a questionnaire that collected demographic information such as eye color and age. The participants were asked to wear an activity and light monitoring band so that daily light exposure and sleep patterns could be analyzed to determine if they played a role in how much the pre-exposure affected the participants. Statistical techniques such as a linear model and a Pearson correlation were used to evaluate the role each of these factors played into the overall non-visual response.

Q3. If there is a cognitive performance improvement induced by a pre-exposure to light, how quickly does it lessen over time?

During the experiment, the SSS was administered at various points during the cognitive testing so that a subjective change in alertness over time could be assessed. Additionally, EEG and EOG were able to record brain wave activity and the occurrence of slow eye movements to provide researchers with a less subjective test of alertness. No analysis was completed on the EEG and EOG data during this research, but the results of the SSS were evaluated using the Wilcoxon Signed-Rank technique to determine the statistical significance of the data.

1.3. Methodology

To measure the effect of pre-exposure to different wavelengths of light (i.e. the independent variable), participants were asked to take part in both the blue and the white pre-exposure treatment on different days. This allowed the data to be paired per participant across the two treatment types. There were four measurements that were analyzed and they provided a means of measuring the dependent variables.

1. Light exposure, activity and sleep patterns from the monitoring band:

This data allowed the study to look at recent patterns in the participant's activities. Daily average light exposure was used to determine its relationship to how participants reacted to the pre-exposure. While not done in this experiment, future work could analyze the amount of sleep in the 48 hours before the experiment to determine if the number of hours of sleep on the experiment day play a role in determining the performance of the participant.

2. Alertness responses from the SSS:

The SSS was provided seven times during each experiment day. Each of those seven responses were compared to the responses given by the same participant on each of

the experiment days. This provided a method for examining the difference in subjective alertness between blue and white pre-exposure.

3. Performance on cognitive tasks

The cognitive tasks used in this research aimed to measure various types of memory and responses that can be seen in human cognition. The following table is a list of the various cognitive tasks used in this study.

Table 1: Cognitive Tasks

Cognitive Task	Cognitive Performance Measure
Reaction time task	Response time
Go/No-go	Response time, Response Control
Stroop	Response Control, Working Memory
Eriksen Flanker	Selective Attention
N-back	Working Memory
Semantic Categorization Task	Semantic Memory

In most of the cognitive tasks, the participant was presented with a stimulus and asked to make a choice between two or more possible responses. These are referred to as Choice Reaction Time Tasks [11]. The one exception to this was the simple reaction time task where no choice between responses was required. Instead, once a stimulus appeared, the participant was given one available response. Due to the nature of the tasks, all of them provided a response time (the time between stimulus presentation and participant response), and all tasks except the reaction time task were able to determine if a question was answered correctly or not (accuracy). Additionally, some tests allowed for congruent or incongruent stimuli. This allowed for analysis of the cognitive improvements when considering congruent and incongruent data. These measurements could be compared between experiment days to determine the difference between the two pre-exposure types.

4. Physiological responses from EEG/EOG

Physiological recordings were taken during pre-exposure and during the low-light condition. Measuring brain waves at different frequencies and the occurrence of slow-eye movements during timed epochs (such as every 30 seconds) allowed for a comparison between the two experimental days. However, the analysis of the physiological data was not completed during this research and is left for future work.

1.3.1. Analysis

Typical daily light exposure taken from the activity band was analyzed using a Pearson Correlation to determine the linear correlation between response time and daily light exposure. A linear model was used to analyze the effect of eye color with the two light conditions. The Wilcoxon Signed-Rank test was used to analyze the SSS and cognitive task data. A Wilcoxon test was used since those two data types were not normally distributed. The signed-rank version of the technique was used since the samples could be paired. Additionally, a linear model was created from the cognitive task data to analyze relationships between features of the test and participant response time.

Since the SSS used ordinal data (data with ordered, natural categories), the effect size was determined using Cliff's Delta. The rest of the data was numerical and did not abide by the rules required for the usage of Cliff's Delta. Instead, the data that was evaluated using the Wilcoxon Signed-Rank test used the Wilcoxon rank correlation as its effect size. The data used in the linear model did not have an associated effect size. Instead, the coefficients of the model allowed for a comparison between the features of the model.

1.4. Assumptions/Limitations

Since participants relied on available volunteers that were associated with the Air Force Institute of Technology, participant demographics were relatively similar. The participant pool consisted entirely of students, interns and faculty members. This resulted in a total of 16 participants that were mostly male (15) holding at least a bachelor's degree in engineering and computer science fields. The majority of the participants were military members (12) between the ages of 25-38 (mean 33.5) with two participants in their early 20's and two participants in their 50's.

As previously mentioned, the 480th ISRW would like to place blue lights in break rooms within their facilities. Since this experiment was intended to mimic their unit's working environment, it is assumed that 30 minutes of exposure to light is sufficient to induce an effect to mimic a potential break time. However, unlike the working conditions of the 480th ISRW units, the experiment was not long enough to evaluate participants for a full work shift with potentially multiple pre-exposure periods during the shift. Likewise, the experiment was not long enough to determine if the effect would continue after repeated exposure over multiple days or weeks. Since this study aims to compare the difference in effect between blue and white light, it is assumed that whichever pre-exposure light color produces the greatest effect would continue to produce the greatest effect after subsequent exposure periods.

In order to prevent the participants from falling asleep during the pre-exposure period, the participants were allowed to read during that time. Since they were allowed to provide their own paper-based reading material this could have induced variation into the experiment due to the nature of the reading material based on its size and the participant's

level of interest in the topic. However, since the chair in the room remained in a fixed position between participants and all participants were required to leave their reading material on a book stand that remained in a fixed position between experiments, it is assumed that the variation was small enough to not need to be accounted for. Maintaining fixed positions between participants forced the participants to look in approximately the same direction with their eyes open. The main difference between participants would have been their viewing angle due their upper body height.

1.5. Key Findings

Most of the analysis results suggest that the white pre-exposure condition caused the participants to perform better on the cognitive tests and to be more alert. However, some of the analysis showed that there wasn't a statistical significance between the two conditions. The overall SSS scores were 0.02 points more alert (on a one to seven scale) in the white light condition than the blue light condition. The most obvious difference came from comparing the change in drowsiness at the start of the cognitive testing to the end of it. From the beginning of the cognitive tasks until the end of the cognitive tasks, drowsiness increased by 0.56 points in the white light condition and 1.13 points in the blue condition.

The cognitive tasks also produced slightly better response times under the white light condition. The Wilcoxon Signed-Rank test showed that under white light pre-exposure, the statistically significant improvements occurred with the Go/No-Go task (average of 26 ms faster response time), N-back task (2-back: 206 ms faster response time, 3-back: 234 ms faster response time) and Stroop task (77 ms faster response time). The Reaction Time Task (RTT), Flanker and Categorization tasks were still faster under

the white condition than the blue condition, but the speed increase was not statistically significant. A linear model showed that performance was improved in the white condition over the blue condition in all models with the exception of the RTT and the Flanker Test. In those two tests, the standard error was too high to ensure an accurate conclusion. Additionally, in all tests where there was a choice between responses, the linear model showed an interaction effect between the pre-exposure light color and the participant choosing the correct answer. Under the white light condition, the difference in response time between correct and incorrect answers was reduced.

Individual daily blue light exposure was analyzed with a Pearson Correlation to determine if the amount a blue light a person receives on a daily basis has any effect on how well the pre-exposure treatment changed a person's response time. For the most part, there was no statistically significant correlation between daily blue light exposure and response time, except in the case of the RTT (r-value of 0.61) and the Stroop task (r-value of 0.56) after the white pre-exposure. A positive correlation indicates that as daily blue light exposure increased, reaction time also increased after the light treatment. Said differently, the more daily blue light a person receives the less likely they are to perform faster on a RTT or Stroop task in the white light pre-exposure condition. Even though they were not all statistically significant, in all cases, increased blue light exposure resulted in a positive correlation with response time (slower). However, since daily blue light was not controlled in this experiment, more work will need to be done to determine if this analysis provides meaningful data.

1.6. Structure of the document

The next four chapters explore the effects of pre-exposure to blue light. Chapter II summarizes existing literature on the non-visual effects of blue light and discusses the research gaps within the topic. Chapter III formalizes the research questions and develops hypotheses for those questions before discussing the experimental outline and analysis techniques. Chapter IV details the results from those analyses. Chapter V provides a conclusion and discusses potential future work in this research area.

II. Literature Review

2.1. Chapter Overview

Until the 1990s, very little was understood about the non-visual effects of light and how light relates to cognitive performance in humans. The discovery of melanopsin in 1998 [12] and the intrinsic photosensitive retinal ganglion cells (ipRGCs) in 2002 [13] led to an interest in this area, but knowledge of how the ipRGCs impart a non-visual effect was still somewhat limited. To fill the gaps, researchers have studied this area extensively and a lot of progress has been made, but there is still a lot of work to be done. This chapter serves to recapitulate findings from around the time of the discovery of the ipRGCs and summarize more recent studies.

2.2. Definitions

To understand the current research in this area, a few topics need to be defined. Those topics include the structure of the eye, chemicals in the body that are affected by light, how light is received and the types of vision.

2.2.1. The Human Eye

It has been well known for many years that the retina of the human eye contains two classes of photoreceptors, rods and cones. The rods are sensitive to low levels of light and are responsible for night vision. In contrast, the cones provide color vision at higher levels of light. The rods are located predominantly in the peripheral retina and provide motion detection. The cones are predominantly located in the fovea; the portion of the eye that provides refined central vision. There are three types of cones that each process different wavelengths of light, S-cones, M-cones, and L-cones that correspond to short, medium, and long wavelengths, respectively [14].

In addition to the rods and cones, there are two other layers of cells in the retina that aid human vision as seen in Figure 1. The middle layer consists of the horizontal, amacrine and bipolar cells which act as a conduit between each other and the other two layers to help regulate the input from multiple photoreceptors. The third layer consists of the retinal ganglion cells which receive the input from the bipolar and amacrine cells in the middle layer before sending the input to the optic nerve.

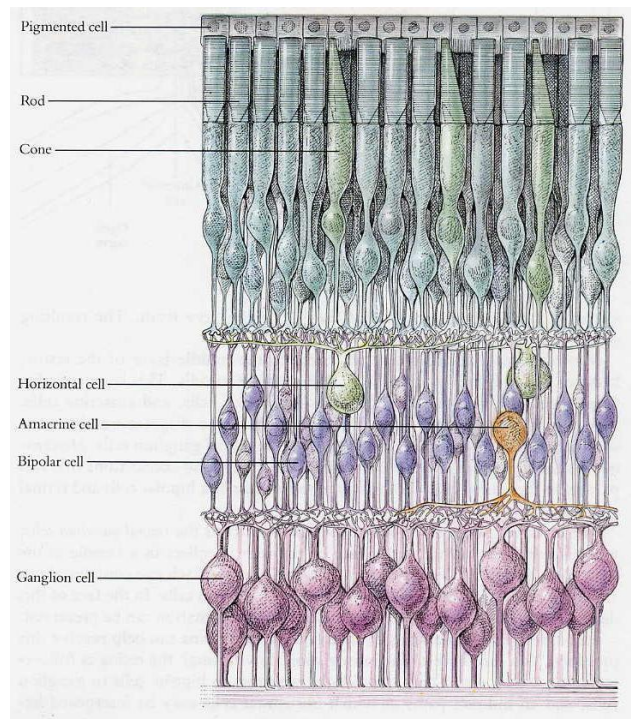


Figure 1: Layers of the Human Retina [15]

Until 1927 it had been assumed that the rods and cones were the only photosensitive cells in the eye. However, when graduate student Clyde E. Keeler found a pupillary response in his blind mice, researchers began to speculate that there may be another unknown photoreceptor in the eye [12]. Unfortunately, most researchers associated the pupillary response with the iris and much of the research in this area halted for many years [12]. Seven decades later, in 1998, a group of researchers decided to study

a photopigment in frog skin to better understand the potential causes of light responses in rodless, coneless mice. During this research, they discovered an opsin in the frog's skin which they named melanopsin. They discovered that this opsin could also be found in the ganglion layer of the retina leading to the idea that the ganglion cells might be photosensitive [12].

It was still a few years later until the photosensitivity of the ganglion layer was proven. In 2002, David Berson and his colleagues showed that ganglion cells expressed melanopsin and were light responsive [16]. They named these cells the intrinsic photosensitive retinal ganglion cells (ipRGCs). However, the entire retinal ganglion layer is not photosensitive. The ipRGCs makeup less than 5% of the total number of retinal ganglion cells [16]. They have somewhat of a unique role in the eye and recent research has shown them to primarily responsible for non-image forming reflexes, circadian rhythm synchronization, brightness discrimination and contrast detection [16].

2.2.2. Sleep and Alertness

The human body responds to light in a multitude of ways. One of those responses is by changes in melatonin secretion levels from the pineal gland of the brain. This is important since melatonin is the chemical in the brain that regulates sleep. Generally, melatonin levels are high at night, and low during the day. However, this may vary depending on the person's sleep schedule. Light has been shown to suppress melatonin production, causing a person to be more alert than with dim or no light. However, it has been noted that participants in various studies have become more alert even without melatonin suppression [17]. Therefore, it is likely that melatonin is not the sole factor in human alertness.

There are two other known factors that regulate a person's sleep patterns and therefore affect alertness: circadian rhythm and sleep/wake homeostasis [18]. Circadian rhythm refers to an approximately 24-hour schedule where humans experience rises and dips in sleepiness. A common indicator of circadian rhythm is seen when humans experience an increased level of tiredness during mid-day and then again at night. Sleep/wake homeostasis is the amount of time since the last time a person slept. As the time since the last sleep grows, the person gets more and more tired. Circadian rhythm and sleep/wake homeostasis work together to regulate sleep patterns in humans.

Sleep inertia (previously referred to as “sleep drunkenness” or post-sleep disorientation [19]) is also an important factor in alertness. It is defined as the lowered cognitive function that occurs after waking up. There are two competing definitions of when sleep inertia has ended. Some experts believe it ends when a person achieves their pre-sleep performance while others believe it occurs when performance has leveled off during the post-sleep period, irrespective of pre-sleep performance [19]. Regardless of the definition, sleep inertia has been shown to impair cognitive performance for as little as 30 minutes, but up to 4 hours after rising [1]. It is always present regardless of the duration of sleep achieved, but abrupt awakening during a slow wave sleep episode tends to result in a longer period of sleep inertia [19]. It is important to consider sleep inertia during lighting studies since sleep inertia can play a factor in early morning human testing.

2.2.3. Vision

There are three different types of vision. Photopic vision is bright or day light vision. This type of vision is primarily provided via the cones. Scotopic vision is night or

low light vision. Scotopic vision is provided via the rods. Mesopic vision is a combination of scotopic and photopic vision. This vision occurs when light is low, but objects can still be seen somewhat clearly. Rods are more sensitive to shorter wavelengths with a peak sensitivity of 500 nm (seen as bluish-green by humans), while the combined cone response is more sensitive to longer wavelengths with a peak sensitivity of 550 nm (greenish-yellow) [20]. Broken out by cone type, the L-cones are more sensitive to 559 nm, M-cones are 531 nm and S-cones are 419 nm [21].

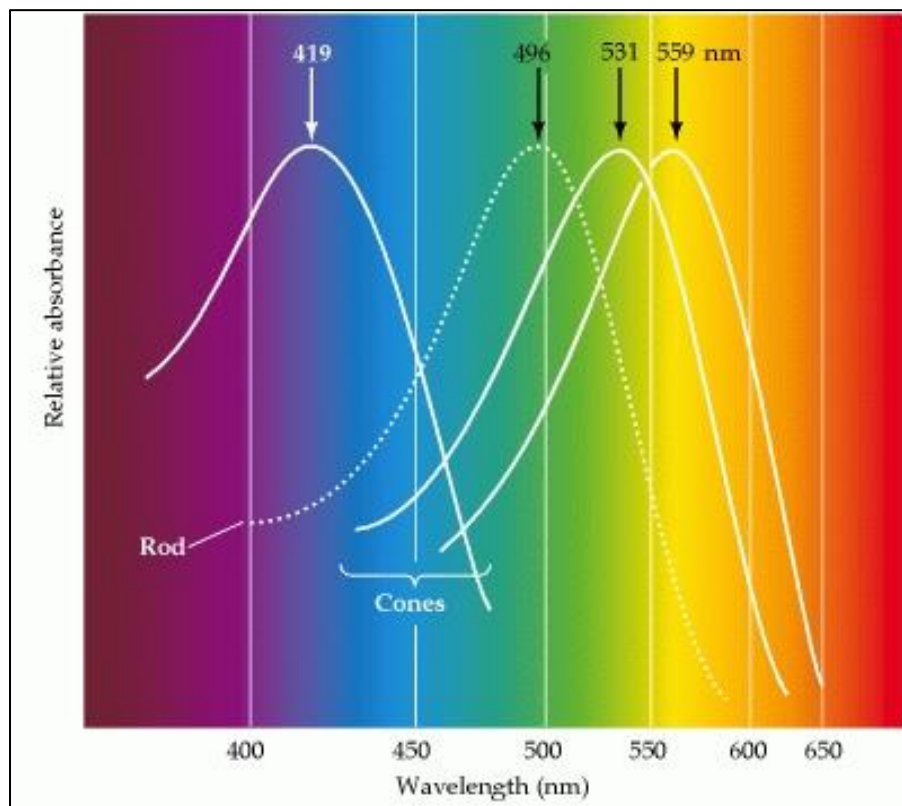


Figure 2: Rod and Cone Peak Sensitivities [21]

2.2.4. Lighting Measurements

Light can be measured in many ways. One of the most basic of those measurements is based on its wavelength in the electromagnetic spectrum. As humans, we visualize differences in wavelengths as differences in color. Visible light is generally

defined to have wavelengths of 400 to 700 nm with the light we have defined to be blue at approximately 475 nm, green at 510 nm, amber at 580 nm and red at 650 nm.

Another important component to measuring light is understanding the types of measurements. The most common measurements used in research and industry are radiometric, photometric and actinometric. Radiometric measurements correspond to the power or energy from the source of the light. Photometric measurements take into consideration the spectral responsivity of the detector or the human eye. Actinometric measurements are essentially the same as radiometric measurements except that the number of photons are measured rather energy. [22]

One of the most commonly used types of light measurements is the amount of light received over an area. This is measured in either illuminance or irradiance. Illuminance is a photometric measurement and is defined as the number of lumens received per unit area (lux). In most of the non-visual light literature, similar radiometric and actinometric measurements include irradiance (W/m^2 or mW/cm^2) or photon flux ($\text{photons/cm}^2 \cdot \text{sec}$) in order to ensure participants are exposed to comparable amounts of photons or energy. Irradiance is defined as “the power of electromagnetic radiation incident per unit area on a surface.” Similarly, photon flux is defined as “the number of photons in μmol per second and unit area on a surface and given in μE (μ Einstein).” [23]

Converting between photometric, radiometric and actinometric units is not as simple as determining the correct constant to multiply the measurement by. Even though radiometric and actinometric measurements don’t need to consider the spectral sensitivity of the human eye, the spectral radiation must be known [22]. However, the process is slightly less complicated for monochromatic conversions where the wavelength is

known. The following formula allows conversion between photon flux and irradiance for monochromatic light: [23]

$$E_{QF} = \frac{N_p}{N_A} = \frac{E \cdot \lambda \cdot 5.03 \cdot 10^{15} \left(\frac{1}{m^2 \cdot s} \right)}{6.02 \cdot 10^{23} \left(\frac{1}{mol} \right)} = E \cdot \lambda \cdot 8.36 \cdot 10^{-9} \left(\frac{mol}{(m^2 \cdot s)} \right) \quad (1)$$

Where:

E_{QF} = Photon Flux

E = irradiance in $\frac{W}{m^2}$

λ = wavelength in m

N_p = the number of photons

N_A = Avogadro's number ($6.02 \cdot 10^{23} \left(\frac{1}{mol} \right)$)

The following is the formula between photometric and radiometric units for monochromatic light using the photopic spectral luminous efficiency curve:

$$\Phi_V = \Phi_E \times V(\lambda) \quad (2)$$

Where:

Φ_V = Photopic measurement

Φ_E = Radiometric measurement

$V(\lambda)$ = Photopic spectral luminous efficiency curve

The conversion between photometric and radiometric units for non-monochromatic light is slightly more complicated, but can be computed via the following formula [24]:

$$\Phi_V = K_m \int_{\lambda=380}^{\lambda=830} \Phi_E(\lambda) V(\lambda) \delta\lambda \quad (3)$$

Where:

Φ_V = Luminous flux in lumens

K_m = Scaling factor (683 lumens per watt)

$\Phi_E(\lambda)$ = Spectral power in watts per nanometer

$V(\lambda)$ = Photopic spectral luminous efficiency function

2.3. Current Research

Since the 1990s, various studies have been performed in the area of blue light research. A lot of discoveries have been made about the non-visual effects of light, but many of these discoveries have led to even more questions. This is likely due to the fact that topic is complicated by the need to measure the effects of light mostly by using subjective measures, and many of the effects are long term and multidimensional. The following section discusses previous and current research on short wavelength light.

2.3.1. Effects

Light has been shown to cause improvements in alertness, mood and response time of study participants. However, shorter wavelengths tend to cause greater improvements. As of 2007, Dr. Cajochen reported that four studies had studied how wavelengths of light affect the alerting response of light. Blue light was shown to increase melatonin suppression and subjective alertness better than green light when exposed to photopic levels of light [1]. Interestingly, blue light caused the participants' pupils to be more constricted than when exposed to green light. This resulted in less light entering the retina, but participants still felt more alert [1]. Another study was completed with pupil-dilated participants which caused an even greater effect in alertness. However, in a separate study it was shown that externally administered melatonin can counteract the alerting effects of light [25].

Core body temperature and heart rate are also affected by light. It is possible these factors are affected by sleepiness, which is then affected by light, but it was shown that blue light created changes in these areas. It was discovered that in the evening when melatonin increases, as blue light slows the production of melatonin, it also slows the

decrease in core body temperature and heart rate (likely secondary effects) when compared to green light and a dark control condition [1].

Another area where light has been shown to have an effect is with working memory and response time. A study was done in 2007 using an n-back task (further discussed in paragraph 2.3.2.2.) that indicated blue light increased working memory when compared with green [26]. However, once the light was switched off, the effects on working memory ceased. The response time improvements from blue light were unintentionally substantiated by another study performed in 2016 that found that pre-exposure to blue light positively affected response time more than amber light. However, in the 2016 study blue light pre-exposure had no effect on working memory via the n-back test [4]. Additionally, another study that compared the effects of blue light and caffeine found that the response time during a Go/No-Go task was improved with a combination of blue light exposure and caffeine. They also discovered that executive function, the ability to suppress inappropriate responses, was not improved [27]. However, aside from working memory, response time and executive function, very few other tests have been performed to show how cognitive performance is affected by light exposure. This opens the door for research focused on how light affects reasoning, intelligence, semantic memory, immediate recall and a barrage of other factors in human cognition.

2.3.2. Measures

There are various ways to measure the effects of light on the human body. Dr. Cajochen summed up a few of these measures in his paper from 2007 [1]. They include electrooculography (EOG), electroencephalography (EEG), sleepiness scales and

cognitive measures. EOG measures eye movements via blink rate and the rate of movement of the eye. Generally, as a person gets tired and less alert, the number of slow eye movements increases and eye blinks slow [10]. Measuring the change in appearance of this phenomenon over time can give an idea of a person's level of alertness. EEG measures brain activity from different frequencies of the brain. It has been shown that EEG activity in the theta-alpha frequencies (or around 4-9 Hz) tends to reduce as a participant gets more alert. Additionally, this phenomenon tends to correspond to light exposure. Various sleepiness scales including the Karolinska Drowsiness Task (KSS) [28] and the Stanford Sleepiness Scale (SSS) [9] subjectively measure a person's current level of alertness. Other alertness measures such as the Epworth Sleepiness Scale [29], Horne-Östberg Morningness-Eveningness Questionnaire [30] and the Pittsburgh Sleep Quality Index Questionnaire [31] measure a person's typical sleep and alertness patterns. These provide subjective measures that can help analyze how a person feels rather than how they perform. Combining these assessments together, it was found that light exposure reduced slow-eye movements, EEG activity in the theta-alpha frequencies and self-reported sleepiness [32]. The final assessment technique, cognitive measures, mainly considers response time and accuracy in tests that are designed to separate and analyze the various aspects of cognition.

2.3.2.1. EEG

EEG is an effective method of determining brain functions, but it generates a lot of data and it is, therefore, important to understand how to analyze it. One of the most important first steps in analysis is removing noise. A common way to do this involves using a reference node during collection that will not be influenced by brain activity, but

will still experience noise from the participant or their environment [33]. Essentially, the signals collected in the reference can be removed from the brain signals. This allows the noise to be removed from the signals of interest.

Much of non-visual light research focuses on how light affects alertness. Frequency analysis of EEG signals has been shown to be somewhat effective in determining levels of alertness by analyzing the theta-alpha (5-9 Hz) range. One method that has been used to do this first requires separating the data into two-second artifact-free epochs. Then, the EEG data is processed using the fast Fourier transform algorithm in 0.5 Hz bins between 1 Hz and 20 Hz [34]–[37]. Finally, the log ratio between each bin and the total EEG power density in the range of 1–32 Hz is found. Figure 3 shows an example of the resulting power density.

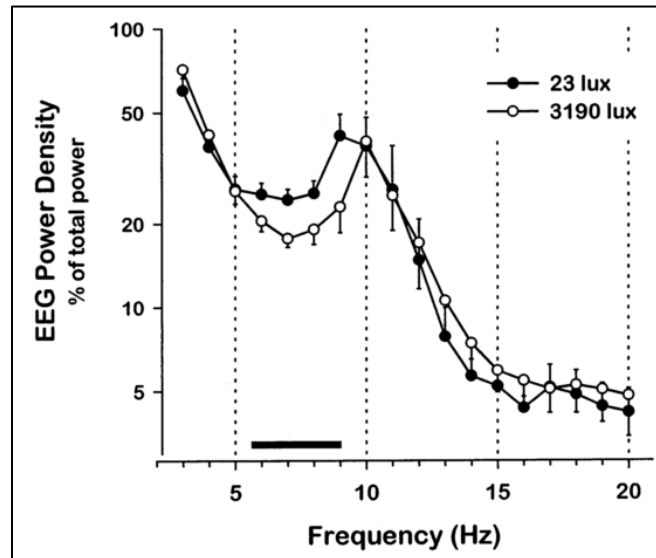


Figure 3: EEG Frequency Analysis [34]

Another common analysis technique is the use of Event Related Potentials (ERPs). An ERP is essentially the average waveform of an EEG epoch that is time-locked to a stimulus [33]. It is typically recommended that there be at least 100ms in the

pre-stimulus portion of the epoch [38], and many experiments use 1400-1700ms post-stimulus to ensure the waveforms can be properly identified and evaluated [39], [40]. The waveform average can be computed for multiple waveforms of the same type such as epochs during congruent stimuli and, separately, epochs during non-congruent stimuli. This allows the response to each type of stimuli to be compared more easily. A benefit to the ERP method is that when averaging the waveform, individual waves that are not consistent to the response (i.e. outliers) should be negated since some inconsistent waves will be positive while others are negative. The average of these positive and negative waves will cancel each other out and result in a zero or close to zero voltage.

The averaged waveforms result in positive or negative voltage which appear as peaks and valleys when displayed graphically. These peaks and valleys are referred to as P or N followed by a number (i.e. P1, N1 or P200) and indicate either the peak's ordinal position or its latency in milliseconds. P represents a positively sloped voltage peak and N represents a negatively sloped voltage peak (or valley). An example of the averaged waveforms can be seen in Figure 4.

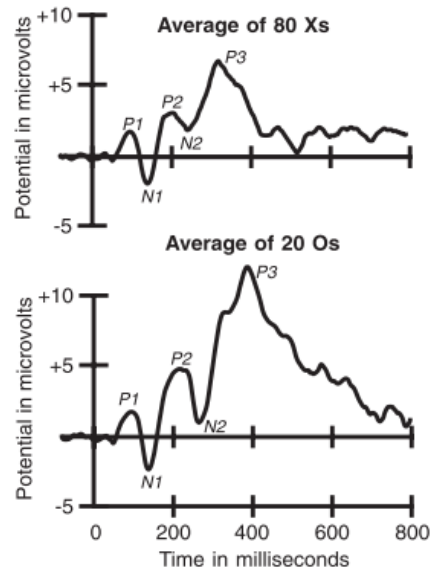


Figure 4: ERP Waveforms [41]

When evaluating alertness and fatigue, the primary peak that is looked at is P3 (or P300). It is generally found approximately 250-500 ms after a stimulus is presented and is thought to be related to decision making [42]. While there is some discussion as to the validity of using P3 to identify fatigue [43], it is generally agreed that fatigue tends to be associated with a lower amplitude and longer latency of the P3 peak most especially with response inhibition [44].

2.3.2.2. Cognitive Measures

In Dr. Cajochen's paper, he discussed a complication that arises when performing lighting studies. Unlike other research topics there are no placebos to control for light. To resolve this issue, it is important to objectively assess the effects of light with cognitive tests such as the psychomotor vigilance test (PVT). However, Dr. Cajochen didn't elaborate further on research that had been done using a PVT. Instead, he pointed out that rather than alertness, PVTs tend to test the participant's sustained concentration. This is a

valid concern that should be mitigated by shorter testing periods when using a mundane and repetitive test.

Regardless of Dr. Cajochen's concerns, various studies have incorporated PVTs in their analysis of lighting effects. The auditory PVT requires the participant to press a button when a chime is heard. Similarly, a visual PVT would require the response when an image is displayed. These two tests are generally used to measure response time. The Go/No-Go test is a type of PVT, except that multiple images/sounds are displayed, but the participant is required to press a button only when the goal image/sound is viewed/heard.

Another common test, the n-back task, measures working memory by asking the participant to remember a sequence of stimuli. These can be any image or sound such as letters, words, images or shapes. The "n" in the n-back task indicates how long of a sequence the participant is required to remember. For example, in the 2-back task, the participant would need to remember a sequence of two stimuli. To verify the participant's ability to remember the sequence, when a new stimulus appears, the participant is asked to identify if the current stimulus matches the stimulus that was shown/heard "n" stimuli previously. Going back to the 2-back task example, if the stimuli "C" and "A" had been shown in that order, the participant would be required to determine if the next stimulus shown was a "C". If it was instead, a "Z" or any other letter of the alphabet, the participant would be expected to identify this stimulus as not being the same.

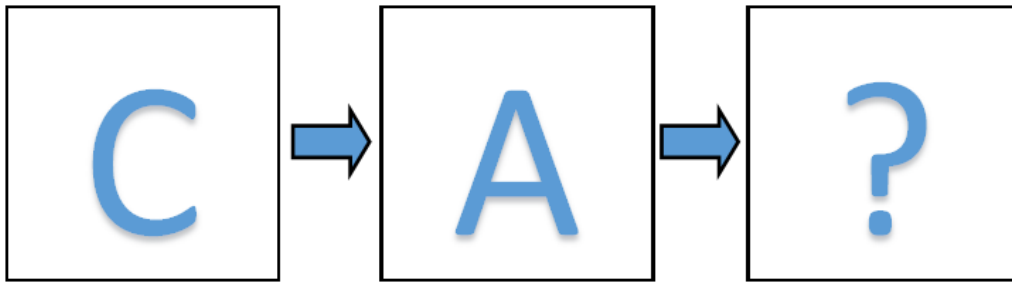


Figure 5: Example N-Back Task

The Eriksen Flanker task shows up in lighting literature often as well. This task is used to test executive functions by showing a number of arrows and asking the participant to indicate the direction of the center or “goal” arrow. The flanking arrows can be either congruent, meaning they are pointing in the same direction of the goal arrow or incongruent, where they are pointing in a different direction than the goal. The intent is how well the participant can identify “goal” arrow’s direction without being confused by the “flankers.”

Studies have shown that response time is improved under blue light conditions with auditory or visual PVTs [45], Go/No-Go and Eriksen Flanker tests [27]. Additionally, it has been shown that accuracy in the Eriksen Flanker test was improved with blue light when comparing results from both before and after light exposure. The same study compared the usage of 240 mg of caffeine with blue and white light. It was shown that blue light and caffeine separately improve accuracy during the Go/No-Go task when comparing performance from before and after exposure. However, when the participants were both exposed to blue light and given caffeine, their accuracy showed no improvement. In other words, the combination of blue light and caffeine causes any improvements found from each independent variable by itself to cancel each other out. The researchers concluded that the participants had exceeded their optimal state of

arousal with either blue light or caffeine and the combination of both caused no improvements to the participants' performance. However, the combination of blue light and caffeine was still shown to be beneficial in regards to response time even though accuracy was not.

2.3.2.3. Time of Day

When Dr. Cajochen wrote his survey in 2007, most of the studies performed thus far had occurred at night. This makes sense since light should have the greatest effect when trying to counteract circadian rhythm, sleep/wake homeostasis, and sleep inertia. These studies proved that light is much more effective at fostering alertness when compared to dim lighting conditions [1]. However, up to that point very few studies had compared the daytime effects of light to the nighttime effects of light.

In 2014, two studies looked at the effects of daytime light exposure. They used EEG, ECG, subjective questionnaires and Reaction Time Tasks (RTT) to analyze their data [45][46]. These studies found that alertness is improved both during the day and at night, and blue light had the greatest overall effect on alertness. Of these two studies, one compared the results of an auditory RTT taken during the day vs at night [45]. It was shown that response time during the day was faster than response time at night, but that light exposure improved response time during the first few minutes of the test regardless of the time of day. Additionally, blue light lowered the rate of response time deterioration and maintained a similar response time throughout the 10-minute test.

In 2016 another study was performed to compare the effects of daytime light exposure with different wavelengths of light [35]. During this study, it was decided to sleep deprive participants over a period of three days in hopes to obtain a more

pronounced reaction to the light. Instead of getting results consistent with previous study, it was discovered that blue, green and dim light had the same effect during the daytime. However, this study used pupil dilation before light exposure and mandating a fixed gaze during light exposure. Additionally, they admitted that the sleep deprivation may have counteracted the effects of the light.

Some additional research is required in order to explore the differences in the studies of daytime vs nighttime effects of light, but it would appear that most research indicates that light has alerting properties during the daytime and nighttime. Since melatonin levels are low during the day, the daytime alerting effects are likely caused by some other unknown factor.

2.3.2.4. Sleep

As mentioned in the previous section, sleep deprivation studies yield results that are not consistent with studies that focus on fully rested participants. A study was performed in 2010 to investigate the ability of light to produce phase shifts in circadian rhythm [47]. During the study, the participants were provided with only four hours of sleep per night over a three-day period followed by (or preceding) a full eight hours of sleep per night for three days. It was discovered that light had a reduced effect on shifting circadian rhythm phases in 10 out of 13 sleep deprived individuals than it did on the individuals who received a full 8 hours of sleep per night. Since sleep deprivation causes such a stark difference in the effects of light exposure, it is important to analyze the effects of light on sleep deprived individuals differently than non-sleep deprived individuals.

2.3.2.5. Light Characteristics

As previously mentioned light intensity and wavelength are important features when studying the effects of light. While there are multiple ways to measure light, the most common tend to be radiometric measurements. These measurements are generally used for research, but are not used in industry. In studies performed by Dr. Lockley (2004) and Dr. Rahman (2014), participants were exposed to 2.8×10^{13} photons/cm²/s of monochromatic 460 nm (blue) or 555 nm (green) light for 6.5 hours [37][45]. Similarly, Dr. Segal performed a study where participants were exposed to 3 hours of either narrowband blue (458-480 nm) or green light (551-555 nm) at $2.8\text{-}8.4 \times 10^{13}$ photons/cm²/sec 3.25 hours after waking [35]. Additionally, Dr. Alkozei performed one of the more recent studies exposing her participants to 30 minutes of continuous short wavelength blue light (irradiance = 1.23 mW/cm², illuminance = 214 lux, λ = 469 nm) or medium wavelength amber light (irradiance = 0.35 mW/cm², illuminance = 188 lux, λ = 578 nm) 30 minutes prior to cognitive testing [4]. To compare the irradiance measured in this study to the photon flux of the other studies, Dr. Alkozei's blue light had a photon flux of 2.90×10^{13} photons/cm²/s and the amber light was 9.77×10^{12} photons/cm²/s. Most other studies seem to fall within this intensity range and wavelength when performing studies on light.

2.3.3. Challenges

The number of challenges in light research are numerous. One major issue is due to the fact that subjective measurements reduce the objectivity of the research. Much of light research involves determining the effect it has on humans. Measuring those effects can vary widely based on the individual. This is especially true as the effects of blue light

become more well-known and the placebo effect becomes more of an issue. Additionally, there are many variables in determining the effect of light. As seen from previous studies, sleep deprivation can cause anomalous results. However, there is no measure to determine what levels of sleep deprivation make light treatments ineffective. It is especially difficult because it is nearly impossible to tell which other nuisance variables could disturb the results.

Additionally, there is a lot of conflicting information. For example, the results from EEG data are not fully understood. Most studies agree that increased alertness results in decreased power of the theta-alpha (5-9 Hz) and delta-theta (0.5-5.5 Hz) frequencies [1], [6], [27], [30]–[32], but there are inconsistencies when it comes to the alpha band (8-12 Hz). Dr. Rahman stated in his paper that “The nighttime alerting effects were associated with an increase in high-frequency alpha EEG activity, considered a specific marker of the circadian drive for alertness, whereas daytime short-wavelength light exposure was not” [45]. Dr. Lockley agreed with this statement in his 2006 paper [37]. However, Dr. Sahin found the opposite results in 2014 stating that “A significant increase in alertness, as measured by a reduction in alpha power, was observed after participants experienced the white light condition, more so than after the dim light condition...” [17] While high-frequency alpha is only a portion of the alpha band, generally considered to be between 9.5-12 Hz, Dr. Sahin uses the entire alpha band shows the opposite of other studies. Additionally, in a 1999 study performed by Dr. Cajochen, it was found that there wasn’t a significant correlation between sleepiness and power in the alpha band [10]. Finally, another study from 2016 failed to correlate light

exposure and EEG power density in any of the bands except at 11 Hz [35]. These inconsistencies make it difficult to make assumptions about light and its cognitive effects.

Another important factor to consider during the daytime studies of light is the amount of sunlight exposure prior to the study. A few studies have attempted to negate or track this issue with wearable light tracking devices, blue light blocking glasses, early morning testing or by forcing the participant to arrive at the testing location while it is still dark. Each of these methods creates a potential challenge. The light tracking devices are known to receive less light than the eyes due to their location on the wrist. Blue light blocking glasses generally do not shield the entire eye from blue light. In the early morning, sleep inertia is an issue as melatonin levels are continuing to drop as the person becomes more alert. The natural alerting effects during the day can get confused with the alerting effects caused by the study's light exposure. Each of these challenges must be considered and accounted for during research.

2.3.4. Areas of Uncertainty

Due to the need to work with humans who vary greatly from person to person, one of the major challenges in lighting research is having consistent data. Because of this issue, it is very common to find studies which are in opposition of each other. A prime example of this is mentioned in section 2.3.2.3 where a common proponent of the alerting effects of blue light, Dr. Lockley, was involved in a study during the daytime that did not show that blue light caused an alerting effect [35].

2.3.4.1. Pre-exposure

Only one study completed in 2016 has studied the effects of exposure to blue light *before* a cognitive task rather than during [4]. In this study, the Stanford Sleepiness Scale

(SSS) was used as a subjective means to test alertness. To test brain functionality, MRI data was collected while performing an N-back test. Each participant was tested relatively early in the morning to avoid excess blue light exposure from the sun, and then provided with a 30-minute wash-out period of amber light exposure before being exposed to blue light (experimental group) or more amber light (control group). Then, there was a 40-minute break between the blue light exposure and the start of the N-back test while the participant was placed in the MRI scanner.

While test accuracy was relatively similar between the control and experimental group, the response time was significantly faster for the experimental group. To determine if the blue light caused the experimental group to be more efficient in the task, the investigators calculated cognitive throughput. Cognitive throughput was calculated as $\left(\frac{\text{Accuracy}}{\text{Mean ReactionTime(ms)}} \right) \cdot 1000$. They used this to find the number correct responses per unit time. Using cognitive throughput, the researchers found that blue light pre-exposure caused improved cognitive throughput over the amber control light. They concluded that while accuracy by itself is not improved with blue light, after blue light pre-exposure participants are able to be correct more often.

Working memory was the only test completed by the study. Since it seems apparent that blue light has an effect on response time, it may be important to test other cognitive measures after pre-exposure to blue light such as reasoning, intelligence, semantic memory, immediate recall and executive function. From the results of previous research, there may not be an effect, but demonstrating this fact to ascertain the expected results would help in resolving some of the inconsistencies in lighting research.

2.3.4.2. Demographics and Other Variables

Research has indicated that demographics can alter the effect of light on a person. In one experiment, younger adults were better at preserving a negative mood in a more reddish light whereas older adults were better at doing the same in a bluish light [49]. Another study looked at how demographics are affected by various types of white light [50]. One study found a statistically significant correlation between blue-eyed participants and faster response times in a visual RTT during exposure to blue light [27]. However, since this was not the intent of the study and the participants were not evenly split between blue and non-blue-eyed participants (7 blue, 14 non-blue), this should only be looked at as an observational study and more work will need to be done to determine if the relationship is valid.

Another study that looked at the effect of blue light blocking glasses had participants refrain from drinking caffeine (a known stimulant) and eating bananas, cheese and turkey (known sedatives) 12 hours before testing [51]. There was no reference or explanation for this design decision. The reason behind it was left up to the reader's interpretation. Since no other studies have analyzed the interaction between consumables and the non-visual effects of ambient lighting, a further analysis of the interaction would be beneficial to the research area.

Finally, another study asked participants to be exposed to a different wavelength of light before the 515 nm (green) light treatment and found that longer wavelength light caused participants to respond better to the treatment [52]. The results of this study imply that either the lack of short wavelength light causes subsequent exposure to short

wavelength light to be more effective, or it implies that humans need short wavelength light to maintain higher levels alertness and higher levels of cognition.

2.4. Research Gaps

The following section discusses areas that have either not been studied or areas where analysis has shown conflicting information. These are research topics where further attention could improve human knowledge on the non-visual effects of blue light.

2.4.1. Demographics

As mentioned in section 0, demographics add some variation to the effects of light that are difficult to explain. For the most part, differences among humans are considered nuisance variables and are accounted for or controlled for in various ways. However, when it comes to determining how to best use light treatments to improve human welfare, determining exactly how each nuisance variable interacts with the non-visual effects of light can aid in finding the best course of action when using light. A possible research area may be to look at all of the possible variables that participants bring to the table (gender, age, sleep schedule, food intake, prior light exposure). This would be important in order to discover many of the unknown properties that may alter the effects of light. Research could go as far as looking at participant DNA to determine DNA markers that are affected by light in different ways or as simple as looking at the comparison of caloric intake to the effects of light.

2.4.2. Explicit/Declarative Memory

As previously mentioned, working memory has been the most tested measure of cognition in relation to the non-visual effects of light. However, there are other pieces to human cognition that can be evaluated to see if light can create any other non-visual

effects. An example of this is explicit or declarative memory. Explicit memory is one of the two types of long-term memory. It is broken into two categories, episodic memory and semantic memory. Semantic memory is defined as memory that has been learned, whereas episodic memory is memory of experiences [53]. Generally, long term memories begin as episodic, but once the experience of learning a fact has been forgotten, they become semantic. While it has been shown that white LEDs can improve explicit memory when compared to white cold cathode fluorescent lamps [54], until 2017 there had been no research to determine if blue light can improve explicit memory [55], [56]. Since this area of research is relatively new, it is definitely an area that needs further review.

2.4.3. Executive Functions

Executive functions (also called executive control or cognitive control) are mental processes used to concentrate or pay attention [57]. They include cognitive functions such as inhibitory control/selective attention, working memory, cognitive flexibility, and reasoning. It has been shown that blue light improves task switching which can be viewed as a form of inhibitory control [58], but executive functions make up various different areas of human cognition many of which have not yet been tested.

2.4.4. EEG

As stated by Dr. Cajochen, the predominant theory within literature is that light causes a reduction of EEG activity in the theta-alpha frequencies [1]. However, further analysis in this area could be useful. A few studies have furthered the analysis of the reduction of activity in the theta and alpha frequencies to correlate with increased alertness instead of increased light exposure. However, as shown in the previous

paragraphs, a few newer studies seem to disagree with this hypothesis. An updated study where as many variables are controlled or researched as possible could remove some of the inconsistencies.

2.5. Summary

Much research has been done since Dr. Cajochen wrote his literature survey in 2007. However, there is still much to understand about the cognitive effects of blue light. Additional research is needed to fully understand the different variables involved in the inner workings of the ipRGCs, the entire spectrum of the non-visual effects of light, and how to use light to improve the human experience. There is promise that light research can aid in fixing the circadian rhythm issues affecting shift workers or could improve the productivity of operators that are forced to work in dim lighting conditions. Hopefully, research in this area will continue so that we can fully understand and appreciate the non-visual effects of light.

III. Methodology

3.1. Chapter Overview

This chapter outlines the methodology for the collection and analysis of data for a human cognitive function experiment. The research discussed in this chapter will provide further knowledge to the human machine teaming community by analyzing the non-visual effects of short-wavelength light. If an effect is found, it may be possible to use various light wavelengths to improve operator alertness and performance.

First, the chapter discusses the research questions and hypotheses. Then, the variables, restrictions and design preferences are outlined. This is followed by a description of the experiment that was performed and the variables that were measured. The goal is to see how cognitive performance changes with exposure to two different light spectrum conditions. Finally, the chapter ends with the analysis strategy that is used in Chapter IV.

3.2. Research Questions

The objective of this research is to determine how pre-exposure to blue light affects the productivity of people who work in low ambient lighting conditions. To reach the objective, this study records alertness and cognitive response with EOG, EEG, subjective alertness measures, and cognitive tests. Since “productivity” is a relatively subjective term, this research needs to clarify which specific actions need to be seen to confirm an increase or decrease in productivity. In this thesis, the clarification is done via various research questions which help to focus the investigation and help to determine which measurements need to be taken. Table 2 outlines the questions.

Table 2: Research Questions

Questions:
1. Does exposure to 30 minutes of short-wavelength light prior to a task improve cognitive performance over full spectrum light?
2. Do demographics such as eye color, age or external factors play a role in the effect of light exposure?
3. Does blue light cause alertness to decrease more slowly than full spectrum light?

As explained in Chapter 2, various studies have shown that blue light tends to provide a greater alerting effect over other wavelengths of light. This has been shown via various cognitive measures which were evaluated by their response time, accuracy and cognitive throughput $\left(\left(\frac{\text{Accuracy}}{\text{Mean ReactionTime(ms)}} \right) \cdot 1000 \right)$ [4] in order to look at working memory, response time and various executive functions. This research uses similar evaluation techniques to evaluate reaction time, response control, selective attention, semantic memory, working memory and alertness to analyze many facets of cognitive performance.

As with most performance-enhancing methods, performance will inevitably revert to normal levels over time. However, blue light has been shown to maintain its performance improvements longer than other light colors when measured via performance of an n-back task and Stanford sleepiness scale reporting [26]. Since this research will also record eye movements and EEG signals, in the future, it will be important to see if this translates to those measures as well.

3.3. Hypotheses

Previous research suggests that blue light exposure will provide a greater performance improvement than white light. Most research indicates that response time and cognitive throughput will increase, but accuracy will remain unchanged.

Additionally, blue-eyed participants will likely be more affected by the blue light exposure than other light colors. Specifically, it has been shown that blue-eyed participants tend to have larger improvements in response time than participants with other eye colors.

Table 3: Research Hypotheses

Hypothesis:
Response time will improve with blue light exposure over white light exposure
Accuracy will stay the same between blue and white light exposure
Cognitive throughput will increase with blue light exposure
Blue-eyed participants will show greater response time improvements with blue light than non-blue-eyed participants
Self-reported sleepiness will increase over time after light exposure, but sleepiness will increase more slowly after blue light

3.4. Independent Variables

This section discusses the independent variable or the variable that was intentionally manipulated. In this research, the main concern was the change in light wavelength. Therefore, there is only one independent variable.

Light color: The main basis of this experiment is to determine how blue light effects the alertness and overall cognitive performance (accuracy and response time) of an individual when compared to white light. Therefore, a 30-minute treatment of full spectrum D6500 white light and short wavelength (approximately 460 nm) blue light was given to participants.

3.5. Dependent Variables

A dependent variable's value depends on the independent variable and essentially represents the outcome that is being studied. In this research, various measures and tasks are used to gain insight into the dependent variables. Table 4 outlines the dependent

variables and their associated measures. The way these measures are actually operationalized within the experiment will be further explained in section 3.10.

Table 4: Variables and Measurements

Dependent Variable	Associated Observables	Associated Measures
Response time	Average Response time (ms)	Reaction time; Go/No-go
Response Control	Average Response time (ms), Response Accuracy (%)	Go/No-go, Stroop
Selective Attention	Average Response time (ms), Response Accuracy (%)	Eriksen Flanker
Working Memory	Average Response time (ms), Response Accuracy (%)	N-back, Stroop
Semantic Memory	Average Response time (ms), Response Accuracy (%)	Semantic Categorization
Alertness	Score (numbered 1 to 7)	Stanford Sleepiness Scale

Response Time [59]: This is also referred to as mental chronometry or speed of processing. It is the amount of time it takes for the brain to perceive and respond to a stimulus. The stimulus can be either audible or visual; in this research a visual stimulus is used. The value is the number of milliseconds it takes the participant to respond after experiencing the stimulus. Response time is affected by a person's level of alertness and their knowledge of the topic. Thus, if a person doesn't know how to perform the task well at the start, but improves over time, a change in response time may appear (learning effect).

Response Control [57]: Response control or impulse control is the person's ability to resist an urge to respond incorrectly. Impulse control can be important once a habit is formed. After experiencing multiple similar stimuli, it can be easy for a human to expect similar future events. Being able to make the correct decision by controlling their urges to make a habitual or expected decision demonstrates a higher level of response control.

There are multiple ways to measure this, but in this research the measurements used are accuracy $\left(\frac{\text{correct responses}}{\text{total responses}}\right)$, cognitive throughput $\left(\left(\frac{\text{Accuracy}}{\text{Mean ReactionTime(ms)}}\right) \cdot 1000\right)$ and average response time (time between the Go/No-Go or Flanker stimulus being shown and the person's response).

Selective Attention [60]: Selective attention or attentional control is a person's ability to choose what they pay attention to and what they ignore. Essentially, selective attentional control is an attribute which characterizes how well an individual is able to filter distractions. While this is similar to response control, it is also slightly different since selective attention doesn't necessarily require a person to break a habit. It can be measured with accuracy, cognitive throughput and response time.

Working Memory [57]: This is an executive function that is defined as the ability to use short term memory to complete a task. A participant is exposed to a stimulus that they will have to remember over a period of time. After the time has passed, they are asked to recall the information. Measures for this variable are accuracy, cognitive throughput and response time.

Semantic Memory [61]: The ability to use memory that is not associated with a personal experience. This is in contrast to episodic memory which is associated with a personal experience (i.e. knowing that a stove is hot vs remembering the one time a stove was touched when it was hot). Often memories will start as episodic and become semantic. To test this form of memory, a participant is prompted to recall something they have learned in the past. A prime example of this is the categorization of objects and animals. While it can't be completely guaranteed that a person will only be using

semantic memory in identifying the image (say, for example, an image reminds them of their pet), asking the participant to categorize the image will remove the personal experiences of the image [62]. Measures for this variable are accuracy, cognitive throughput and response time.

Sleepiness [9]: The responses to a subjective sleepiness scale were compiled. Measures for this variable are the difference in responses between the two pre-exposure light conditions.

3.6. Control Variables

The following discusses the constant variables or the variables that the experiment will make every effort to keep the same throughout the trials.

Exposure time: Each light treatment lasted 30 minutes. Maintaining a constant exposure duration ensures that the amount of time of light exposure is not a source of variance in alertness and performance. Exposure to blue light on the computer screen during the test was also constant in both conditions.

Exposure activity: During pre-trial exposure to light, the participant must be kept active, but not to the point of exhaustion. This is to mimic the participant taking a break from work, but not sleeping. The participant will be allowed to read and must keep their eyes open for the duration of the exposure phase.

Exposure intensity: During the treatment, participants were exposed to 200 lux of either blue or white light. Lighting conditions were calibrated before the experiment to ensure consistent intensity in each condition.

Exposure angle: The room where the participants were working has a wall in front of them and a ceiling above them with multiple LEDs. Additionally, there was a diffuser

to spread the light and reduce glare of the individual LEDs. The same LED strips were illuminated in the white and blue conditions.

3.7. Nuisance Factors

Nuisance factors due to the differences between people are an issue in most human experiments. Many of these nuisance factors were mentioned in section 4.3, but they deserve further discussion. Table 5 outlines potential nuisance factors and mitigation strategies.

Table 5: Nuisance Factors

Nuisance factor	Mitigation Strategy	Anticipated effects
Sunlight exposure (Measured in W/m ²)	Ensure participants are scheduled for testing no more than 3 hours after waking. Measure light exposure with activity band so that the amount of light exposure can be considered during analysis Ask participants to not exercise or spend excessive amounts of time outdoors the morning of the experiment Note: blue light blocking glasses will not be used since it was found that blue light can still enter the eye via the peripheries.	It is expected that sunlight will still have some effect. The amount of the effect is unknown.
Demographics and habits can affect alertness	With enough participants, these effects should be negated Since it is not clear how these effects relate to the ability of the human body to use the effects of blue light, these effects were ignored but recorded.	Varies
Learning Effect	The experiment design was counterbalanced: Alternate participants between being exposed to blue light first and white light first	Learning effect will likely affect response time and accuracy
Difficulty between trials may not be the same	Randomize tests that can be randomized Tests that cannot be randomized will also be altered back and forth similar to the strategy to combat learning effect	Unknown – since it is a subjective measure, it is impossible to determine with absolute certainty if one version of a test is harder than another.
Sleep	Ask participants to maintain normal sleep patterns Ask participants to fill out sleep study questionnaires to determine if normal sleep patterns are maintained for the experiment Participants wear activity band to verify sleep between experiment days	Sleep deprivation negates the effects of blue light. The goal is to reduce this factor.
Habits that effect alertness	Ask participants to refrain from caffeine usage, nicotine usage or exercise during the morning of the experiment In case participants refuse to refrain, annotate the amount used	This could potentially cause withdraw and negate the effects of the IV, but will help to keep participants under similar conditions
Time since waking/period in circadian rhythm	To avoid sleep inertia, participant will be given a questionnaire about their normal wakeup time. Participant will be scheduled between 1 and 3 hours after they wake up.	This should negate sleep inertia, but also provide extra blue light exposure. This extra blue light exposure could negate some effects but is also indicative of real world conditions.

3.8. Restrictions

Since this research involves human participants, there were multiple restrictions. The biggest restriction was on the duration of the experiment. We were limited to asking participants to be willing to volunteer their time without any compensation. It would have been useful to test other lighting conditions for comparison (such as amber colored light), but since this experiment relied heavily on the availability of the volunteers, asking people to dedicate more than just a few days to the experiment was not possible. Additionally, since this test was designed to see how well short wavelength light affected the cognitive performance of an analyst during their work shift, it also would have been interesting to monitor an analyst for an entire 8 to 12-hour shift. However, access to intelligence analysts was not available for this research.

Individual differences in humans also add a lot of variability to an experiment. Emotions, stressors, thoughts, differences in people's personalities, boredom and multiple other factors all influence the outcome of the experiment. While participants can be asked questions about their habits and current lifestyle to try to discern what may affect their sensitivity to blue light, not all possible effects can be covered since many are unknown.

3.9. Design Preferences

Replication is the best design preference during this experiment. Repeating the experiment among multiple participants will reduce the effect of individual differences in participants since each participant's performance will be compared to their own performance under a different light condition. Additionally, randomization will be used during the creation of the cognitive tests to ensure participants aren't exposed to the same test during each experimental day.

3.10. Experiment

In accordance with approved IRB protocol FWR20170085H v1.01, the research questions were evaluated by conducting a within-participant human experiment. The study was run with one control condition and one experimental condition. The control condition consisted of exposure to 30 minutes of white light prior to various cognitive tasks. In the experimental condition, participants were exposed to the same duration of blue light prior to the tests. The tasks consisted of multiple cognitive response tasks presented in the following order: reaction time task (RTT), Go/No-Go, Eriksen flanker, n-back, semantic categorization, and Stroop. The participants were required to complete the study between one to three hours of waking to maintain similar levels of melatonin and solar blue light exposure while also avoiding sleep inertia. To measure the differences in participants on the days prior to the test, they were asked to wear an activity band that measured periods of sleep and light exposure during the 48 hours prior to experiment participation.

3.10.1. Participants

Sixteen participants were involved in the study. There were 15 males and one female with ages between 21 and 56. The average age was 33.5 years with a standard deviation of 9.0 years. Of the 16 participants, one was left handed. All others were right handed. Six individuals had blue eyes, four had brown, four had hazel, one had green and the last individual refrained from answering. Nine wore corrective lenses for computer work at least some of the time and two others had undergone eye surgery to correct their vision. All but four of the individuals used caffeine on a regular basis. On average, they normally received about 7.4 hours of sleep each night with a standard deviation of 0.96

hours. There was one participant who was an outlier in regards to sleep duration. That participant received four to five hours of sleep each night. Without that participant's data, the average hours of sleep were 7.5 hours with a standard deviation of 0.62 hours.

3.10.2. Experiment Sequence

The experiment was partitioned into three sessions spanning at least five days. Day one was the training day where, after signing the informed consent document, the participants were given instructions, allowed to practice the cognitive tests, and were issued the activity band. Days two and three did not have to occur immediately following day one, but for the 48 hours prior to the participant returning for day four, participants were asked to wear the band. They did not need to visit the lab on those two days. Day four was the first experimental day where the participants were given the treatment of either blue or white light (alternating with each subsequent participant). Day five was a repeat of day four except that the participants were given a different color light treatment than the previous day. Day five did not need to occur immediately after day four, but the participant must have worn the activity band continuously for at least 48 hours prior to returning for day five. The 48-hour period of band wear for day five could be concurrent with the 48-hour wear for day four, but didn't have to be if the participant was unable to return to the lab for an extended period. In most cases, this meant continuous wear of the band from day two until the end of the experiment on day five. For the exceptions to the continuous wear, there was at most a 12-day period between band wear. Figure 6 shows the schedule that the participants adhered to.

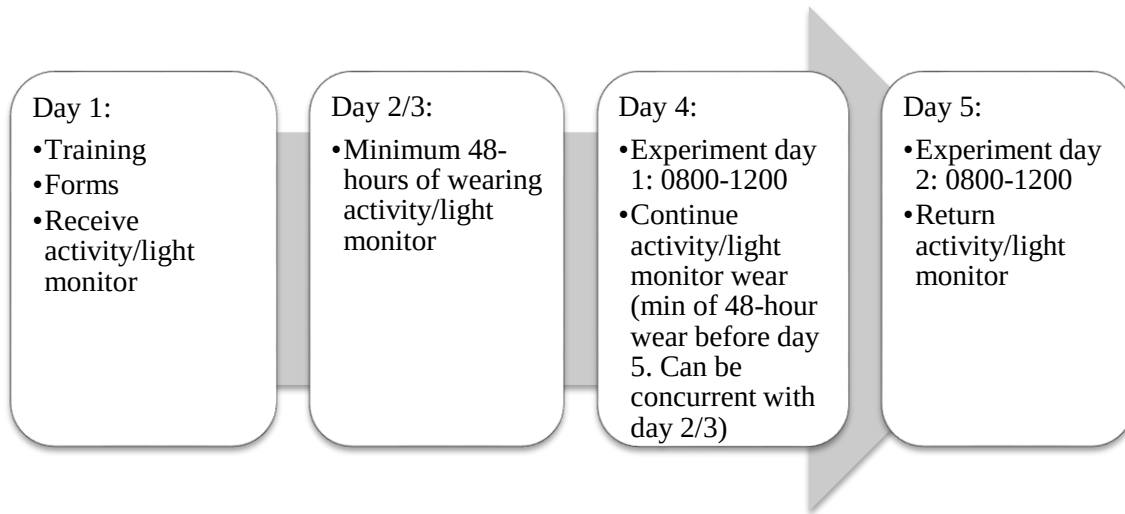


Figure 6: Experimental Schedule

3.10.2.1. Experiment Training – Day 1

At the start of the training day, the participants were asked to sign the informed consent document for approval to participate in the experiment. Once signed, they were administered the Ishihara color deficiency test [63]. This test was used to determine if the participant was able to differentiate between the colors used during the cognitive tasks. Participants that failed the color deficiency test were excluded from participation. Upon successful completion of the color test, each of the cognitive tests were explained and practiced until the participants were comfortable with the tasks. Participants were permitted to practice the tests as many times as necessary.

Afterwards, participants were asked to fill out multiple surveys to categorize their typical sleep patterns and alertness. The main questionnaire asked various demographic and lifestyle questions, as shown in Figure 7.

Blue Light Study Pre-Experiment Questionnaire		ID: _____
Age: _____	Sex: _____	Handedness (left, right, both): _____
Eye Color: _____		
Do you wear corrective lenses when performing computer work?		☐ Yes ☐ No
Have you ever had eye surgery?		☐ Yes ☐ No
If so, why? _____		
When did you have eye surgery? _____		
Please check any of the following habits that may affect your alertness?		
____ Caffeine use:	Amount per day: _____ Type: _____	
____ Medications:	My medication makes me (circle one): dowsy more alert	
____ Smoking:	Cigarettes per day: _____	
____ Sleep Disorders		
____ Sleep deprivation		
How many hours do you typically sleep each night? _____ hours		
What is your usual wakeup time? _____		

Figure 7: Pre-Experiment Questionnaire

To get a sense of the participant's sleep habits and general alertness, the participants were administered the Morningness-Eveningness Questionnaire [30], the Pittsburgh Sleep Quality Index Questionnaire [31], and the Epworth Sleepiness Scales [29]. These scales and the pre-experiment questionnaire were used to select the best time for the participant to return for the experimental days. The day and time selected intended to minimize sleep inertia and solar blue light exposure by asking participants to arrive for the experiment days between 1 to 3 hours after their normal wake-up time. Finally, they

were given the light monitoring band to wear 48 hours prior to returning for the experimental days. Participants were then asked to refrain from caffeine, exercise and tobacco on the morning of the experiment. However, they were told the use of those substances wouldn't preclude them from the study and should they choose to use them, to keep the usage the same on both days

3.10.2.2. Experiment Day – Days 4 and 5

During the experimental days (days four and five), the participants were first asked to fill out a survey. The survey asked questions about caffeine, food and beverage intake over the last 24 hours. The survey can be seen in Figure 8. This questionnaire will be important in ensuring that caffeine usage did not play a part in alertness.

Blue Light Study Pre-trial Questionnaire		ID: _____
Have you done anything in the last 24 hours that may affect your alertness today?		
____ Caffeine use:	Amount: _____	Type: _____
____ Medications:		
____ Smoking:	Number: _____	
When did you go to sleep last night? _____ Wake-up this morning? _____		
Did you wake up last night in the middle of sleep? If so, how many times (approx.): _____		
What did you eat/drink last night? _____		
What did you eat/drink this morning? _____		

Figure 8: Pre-trial Questionnaire

At this point the participant was asked if they needed to take a break before getting started. Once they were ready, the EEG and EOG devices were placed on the individual. The sensor application process is explained in section 3.10.3.2. After the EEG was checked for correct functionality, the exposure phase started. During this time, the

participants sat in the light exposure room and were asked to sit relatively still while being exposed to either blue or white light. They were permitted to read a paper book or document which was kept in a fixed location for each participant.

After the treatment, the participants were asked to perform various cognitive tasks in a low-lit room to determine the effects of the light treatment. The tasks consisted of a simple RTT, the Go/No-Go, Eriksen Flanker, N-back, semantic categorization and the Stroop task. These will be explained in a later section. During this time, the participant continued to be monitored via EEG and EOG. Response time and correct answers for each task were taken for each cognitive task.

There were two versions of previously mentioned tests that were evenly spread among participants. This resulted in 8 participants taking test version 1 with the blue exposure and 8 other participants taking version 2 with the blue exposure. The participants, then, took the opposite test version number with the white condition. To prevent memorization of the test, the test version that the participants received first was also spread evenly among participants. The actual breakout of participant to pre-exposure colors and test versions can be seen in Table 6.

Table 6: Participant Test Version & Pre-exposure Data

<i>ID</i>	<i>Day 4</i>		<i>Day 5</i>	
	Color	Version	Color	Version
1336	blue	1	white	2
2436	blue	1	white	2
6208	blue	1	white	2
9672	blue	1	white	2
2767	blue	2	white	1
6336	blue	2	white	1
7523	blue	2	white	1
9110	blue	2	white	1
4836	white	1	blue	2
6039	white	1	blue	2
6600	white	1	blue	2
8828	white	1	blue	2
2339	white	2	blue	1
2861	white	2	blue	1
5435	white	2	blue	1
7211	white	2	blue	1

3.10.3. Equipment and Setup

This section details the equipment and the testing environment including setup, measurements, and restrictions. It further clarifies use of the activity band, the EEG/EOG system, the experiment room configuration, and the light calibration details.

3.10.3.1. Activity and Light Monitoring Band

The Philips Actiwatch Spectrum Plus was used to record participant activity and light during the 48 hours prior to returning to the lab. The device used a MEMS type accelerometer with a 32 Hz sampling rate to measure movement. It was also able to measure photopic illuminance, irradiance and photon flux at 400-700nm wavelength. Participants were asked to keep the band on their wrist as much as possible. If removed, the participant was asked to record the date and time of removal in a log. They were

permitted to wear it on either wrist, but asked to keep clothing from covering it as much as possible. Once donned, they were asked to wear the Actiwatch until the end of the final experiment day.

3.10.3.2. Physiological Recording Devices

To collect physiological signals the Cognionics Mobile-72 system was used. This system allows for the collection of up to 72 channels of electrophysiological recordings. However, only 66 channels were required for this experiment. 64 of those channels were dedicated to collecting brain signals and 2 channels were dedicated to collecting eye movements (2 electrodes per channel). Electrodes were placed around the eyes to record eye movements via the electrooculography (EOG) technique. Brain signals were recorded by using the electroencephalography (EEG) method. To perform EEG, a cap with 64 electrodes were placed on the participant's head.

The placement of the EOG electrodes and the EEG cap can be seen in Figure 9 and Figure 10. One set of EOG electrodes were affixed to the participant's temples to measure side to side eye movement. Another set of EOG electrodes were connected to the nasion and under the participant's left eye to measure up and down movement. Additionally, a ground electrode was placed on the participant's left clavicle and connected was shared with the other four EOG electrodes. This setup was selected to ensure eye movement could be accurately collected while not interfering with the electrodes on the EEG cap.

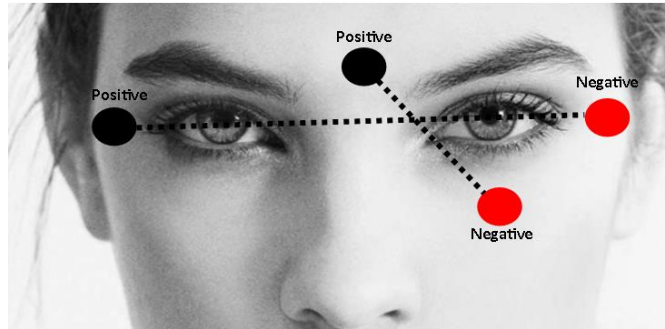


Figure 9: Electrode Placement

The EEG cap seen in Figure 10 was placed on the participant's head with the ground electrode placed below Oz (on the nape of the neck) and the reference electrode on the right mastoid. The placement of electrodes around the cap used the international 10-20 system.



Figure 10: EEG Cap

The physiological equipment setup contained sensing equipment, recording equipment, and an interactive station for the participant. The connections between the sensors, data acquisition system, physiological monitoring computer and stimulus computer can be seen in Figure 11. The Cognionics physiological collection software and cognitive stimulus software ran on two separate computers; however, the stimulus computer was connected to the computer running the Cognionics software wirelessly via

the trigger device. This connection enabled timestamped event triggers to be sent from the stimulus software to the Cognionics software. The Cognionics software labeled the collected physiological data with the synchronizing timestamps in each data collection. Although the physiological computer recorded the physiological data, the data was actually sensed and transmitted to the computer by the data acquisition unit (DAQ) attached to the cap on the participant's head.

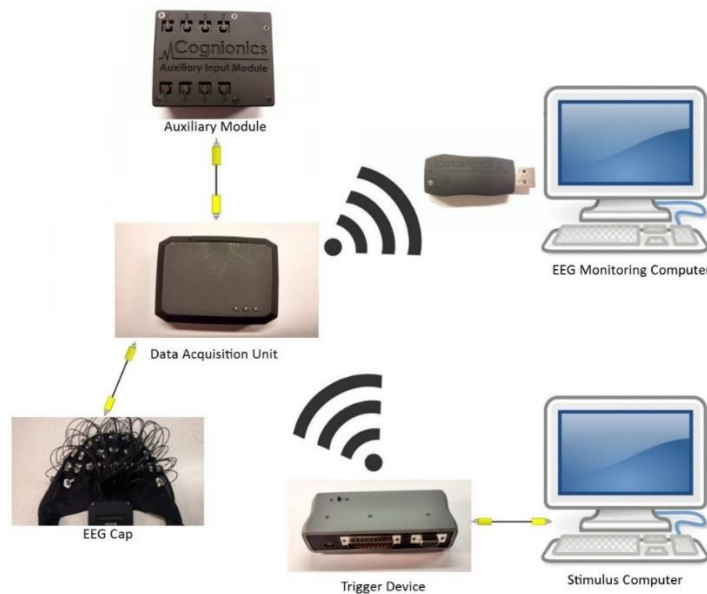


Figure 11: EEG Setup

Participants completed the cognitive tests on the stimulus computer. During the experiment, the stimulus computer sent alerts to the trigger device each time an event occurred that needed to be recorded by the Cognionics software. Events occurred when a new test started, when a new stimulus appeared on the screen or when the participant responded to the stimulus. The trigger device wirelessly sent these alerts to the DAQ which was, then, wirelessly sent to the Physiological monitoring computer. Additionally, the EEG cap sent signals to the DAQ via a wired connection. Similar to the

alerts/triggers, the DAQ sent the EEG cap signals to the EEG monitoring computer wirelessly. The auxiliary module is used to connect EOG, ECG and any other auxiliary device to the EEG monitoring computer. In the case of this experiment, only EOG was used in the auxiliary module. This required two channels with two electrodes each.

3.10.3.3. Experiment Room Setup

During the exposure phase, the participants were placed in a light controlled room. The wall they were facing and the ceiling above them was covered in LED strips as can be seen in Figure 12 and Figure 13. Additionally, a diffuser screen was placed over the LEDs to spread the light around the room. Each LED strip could be individually controlled to create the desired light wavelength and intensity, but each strip was kept at the same setting for this experiment.



Figure 12: Experiment Room

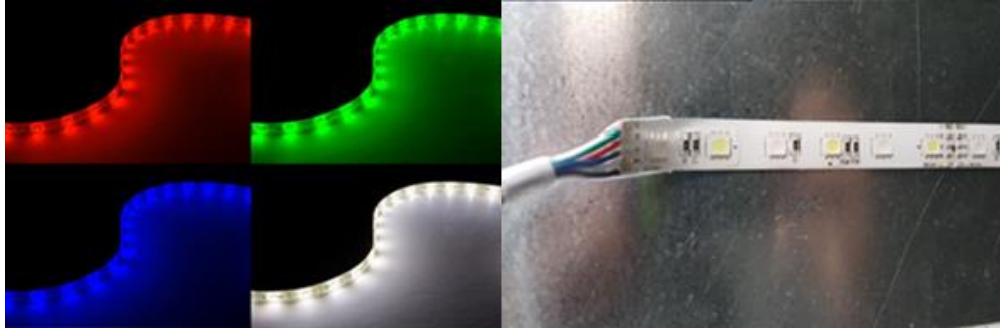


Figure 13: Close-up of LEDs

During the exposure phase, participants were allowed to read a paper book or magazine. The book was kept on a book stand to ensure the all participants' eyes were focused in the same position. Additionally, the chair was maintained in a static position for all participants. The participant was about 140 cm away from the light in front of them and 120 cm away from the diffuser sheet. Depending on the participant's upper body height, they were approximately 110 cm away from the light above them with 15 cm between the light and the diffuser panel. The setup can be seen in Figure 14 where during the exposure phase the keyboard would be replaced with the book holder.

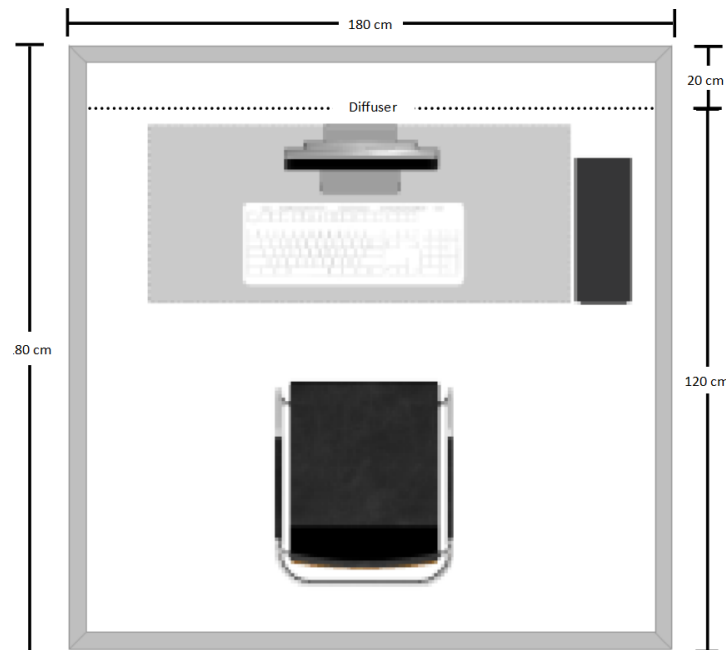


Figure 14: Experiment Room

3.10.3.4. Light Measurements

During the exposure phase the participants were exposed to either blue or white light followed by dim white light while completing the cognitive tasks. The following documents the light measurements that were taken prior to the experiment. Figure 17 is an enlarged version of the dim lighting condition shown in Figure 16 since it is difficult to differentiate the light wavelengths given the much lower light intensity than the blue light condition.

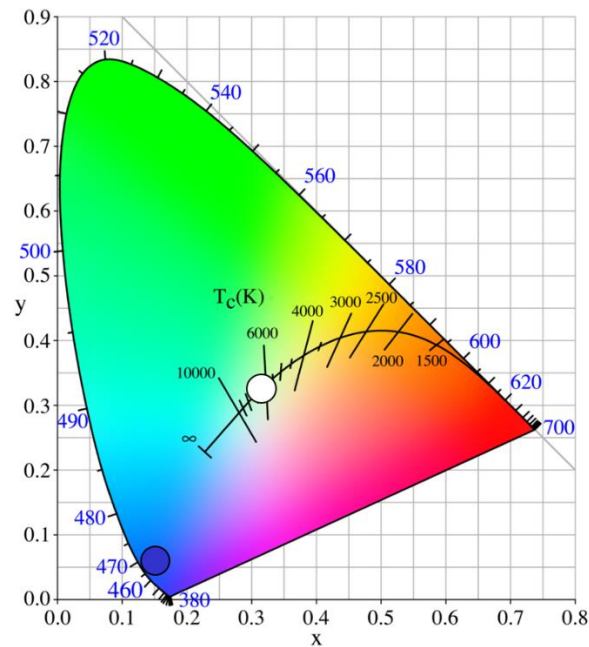


Figure 15: Chromaticity Diagram of Light Treatment

When selecting the white lighting condition, the goal was to mimic typical workplace lighting as much as possible which led to the selection of an illuminance level close to typical office lighting while also being within the energy capabilities of the available LEDs. The illuminance selected was 200 lux (which matches Dr. Alkozei's experiment [4]) for both the blue and white conditions. The illuminance goal for the dim lighting condition used during the cognitive task phase was between 2 to 5 lux to mimic

the light levels experienced when a room is lit with only lights emanating from computer displays. While not necessarily representative of the color of office lighting, the Correlated Color Temperature (CCT) in this experiment very closely matched D65, which is a commonly used standard illuminant for color matching. The lighting measurements were taken with the SpectraDuo Spectroradiometer (model PR-680L) and Konica Minolta T-10 illuminance meter. The readings taken from these devices can be seen in Table 7.

Table 7: Light Measurements

Light Color	Blue	White	Dim White Light
Peak Wavelength	460	630	630
Illuminance (lux)	200	200	3.5
Radiance (watts/sr/m ²)	1.47	0.289	4.43E-03
Photon Rad. (photons/sr/m ² /sec)	3.42E+18	7.93E+17	1.23E+16
Luminance (cd/m ²)	82.22	74.80	1.216
Luminance (fl)	24.0	21.8	0.355
Scotopic Y (cd/m ²)	1,450	238	3.16
XYZ	253.6, 82.22, 1459	70.40, 74.80, 81.13	1.145, 1.216, 1.305
xy	0.1413, 0.0458	0.3110, 0.3305	0.3123, 0.3317
uv	0.1730, 0.0841	0.1961, 0.3126	0.1966, 0.3131
u'v'	0.1730, 0.1262	0.1961, 0.4689	0.1966, 0.4697
CCT		6579K	6498K

When looking at the spectral data in Figure 16 and Figure 17, it is important to see that while all lighting conditions contain blue light, the blue light condition contains a much higher concentration of short wavelength photons (near 464 nm) than the white light condition. The dim lighting condition that is provided after the exposure phase (during the cognitive tasks) has an almost negligible amount of wavelength of light, but as can be seen in Figure 17, which shows the dim light on its own scale it is not completely without spectral power.

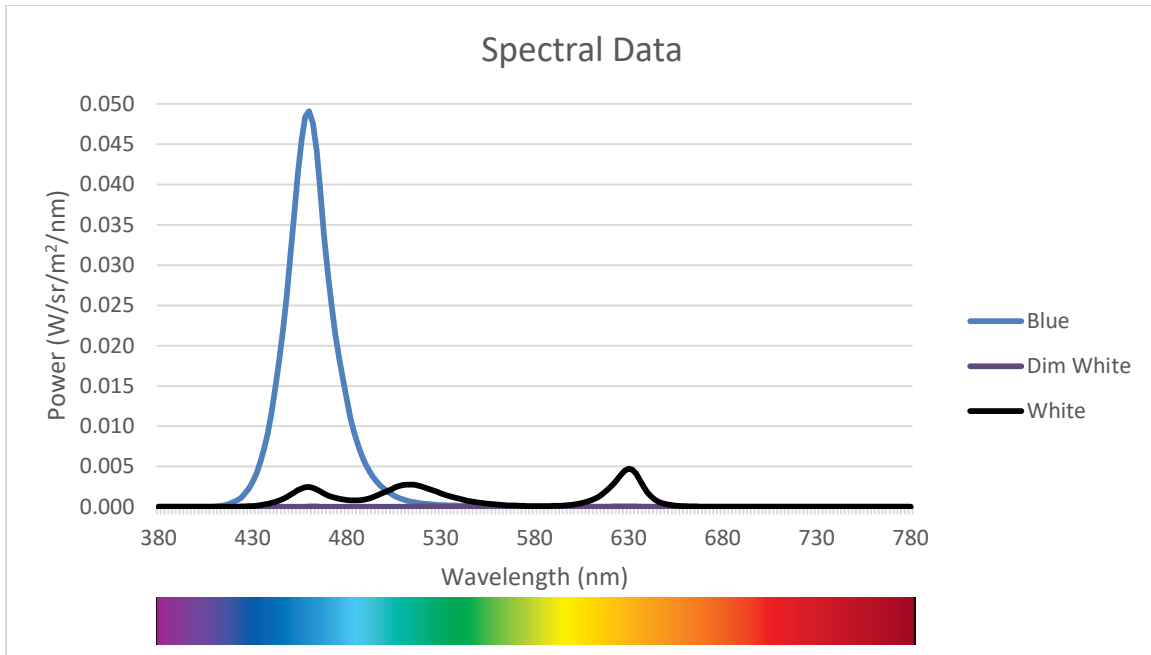


Figure 16: Spectral Data for Lighting Conditions

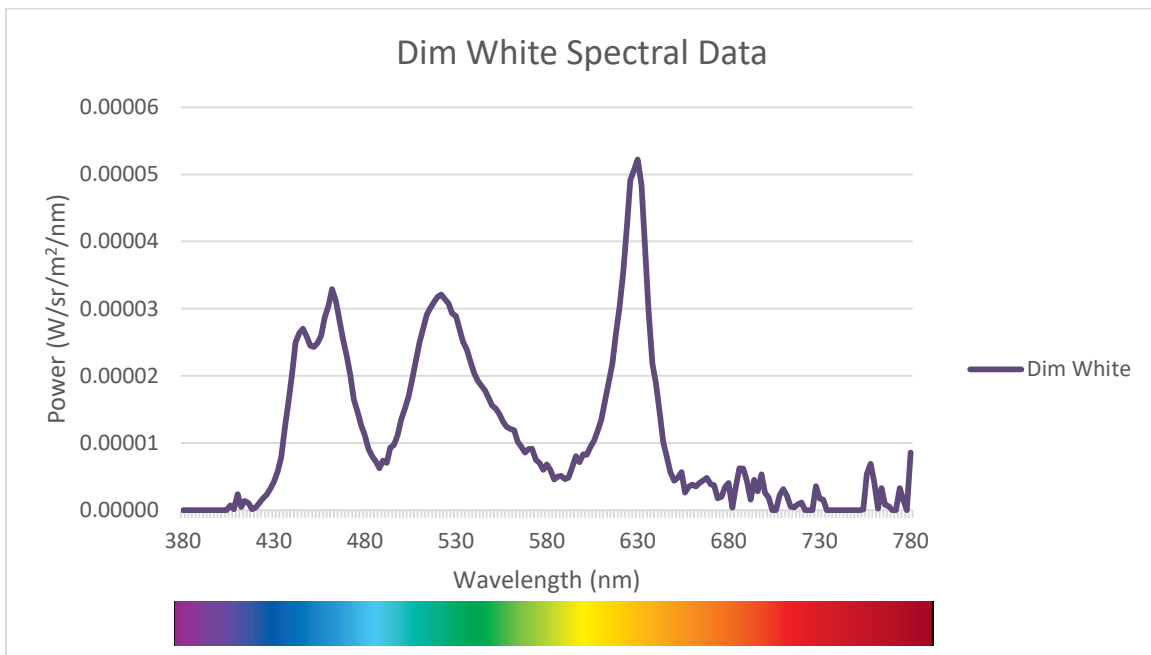


Figure 17: Enlarged Dim White Spectral Data Graph

3.10.4. Measure 1 – Stanford Sleepiness Scale

The Stanford Sleepiness Scale (SSS) [9] allows a participant to self-asses their subjective alertness on a scale from 1 (very alert) to 7 (almost asleep). The standardized

version of this test has option for “asleep.” However, since this option cannot be used by the participant, it was removed as an option in this experiment. The SSS will be used to determine how alert the participant feels, but cannot measure the cognitive effects of this feeling. The test will be administered a total of 7 times during the experiment. One before the cognitive testing begins and then one after each cognitive test. There is not one between the 2-back and 3-back since that section is looked at as one comprehensive n-back task.

Table 8: Stanford Sleepiness Scale

Degree of Sleepiness	Scale Rating
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not fully alert	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

3.10.5. Measure 2 – Simple Reaction Time Task

The RTT is a visual psychomotor vigilance task (PVT). The objective of this task is to respond to a stimulus as quickly as possible. In order to do that, the participant will be shown a screen with a white box in the center. After a randomized delay selected from 1.5, 2 or 2.5 seconds an ‘X’ will appear in the box. Once this occurs, the participant is expected to press the spacebar and the ‘X’ disappears. This will restart the randomized delay and repeat the process. The entire activity continues for 240 seconds (approximately 90 to 100 iterations). If the participant presses the spacebar while no ‘X’ is on the screen, the randomized timer will restart. If the participant refrains from

pressing the spacebar when the 'X' appears, the 'X' will remain on the screen until the participant responds. A graphical representation of this task can be seen in Figure 18.

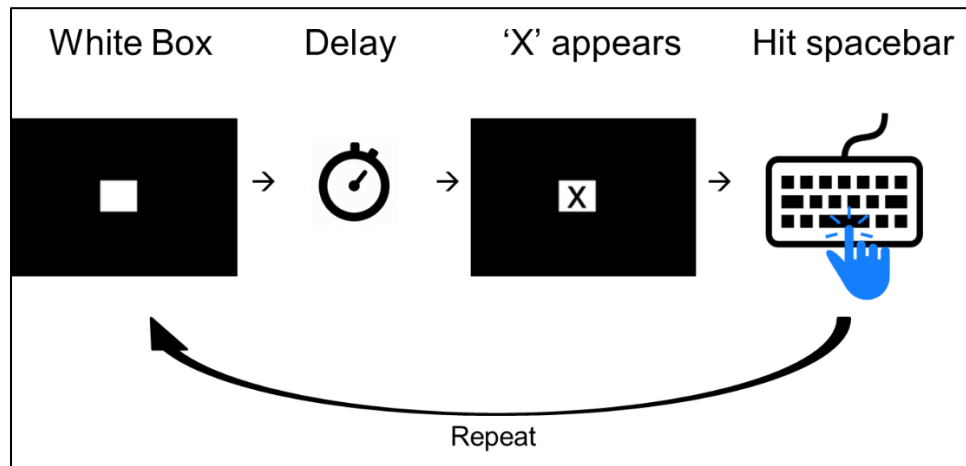


Figure 18: Reaction Time Task

3.10.6. Measure 3 – Go/No-Go Task [64]

In the Go/No-Go Task, the participant is presented with one of three different colored Gabor patches (red, white or blue). The patch appears for 100 milliseconds to the left or right of a fixation point located in the center of the screen. If they see a red Gabor patch, they are expected to press the left control key on the keyboard. For a blue patch, they should press the right control key. If they see the white patch, they should ignore it. Both the blue and red patches appear approximately 40% of the time each. For the remaining 20%, the white patch appears. The intent of this distribution is to create a habit of pressing both the left and right control keys for 80% of the time so that when a white patch appears the participant needs to demonstrate inhibitory control to avoid continuing a key press out of habit. If the participant responds incorrectly or does not respond within 2 seconds on a non-white Gabor patch, the response is counted as incorrect. After the participant responds or 2 seconds have passed, a 1 second pause occurs and a new Gabor

patch appears. This continues for 240 seconds (91 iterations). A graphical representation of this task can be seen in Figure 19.

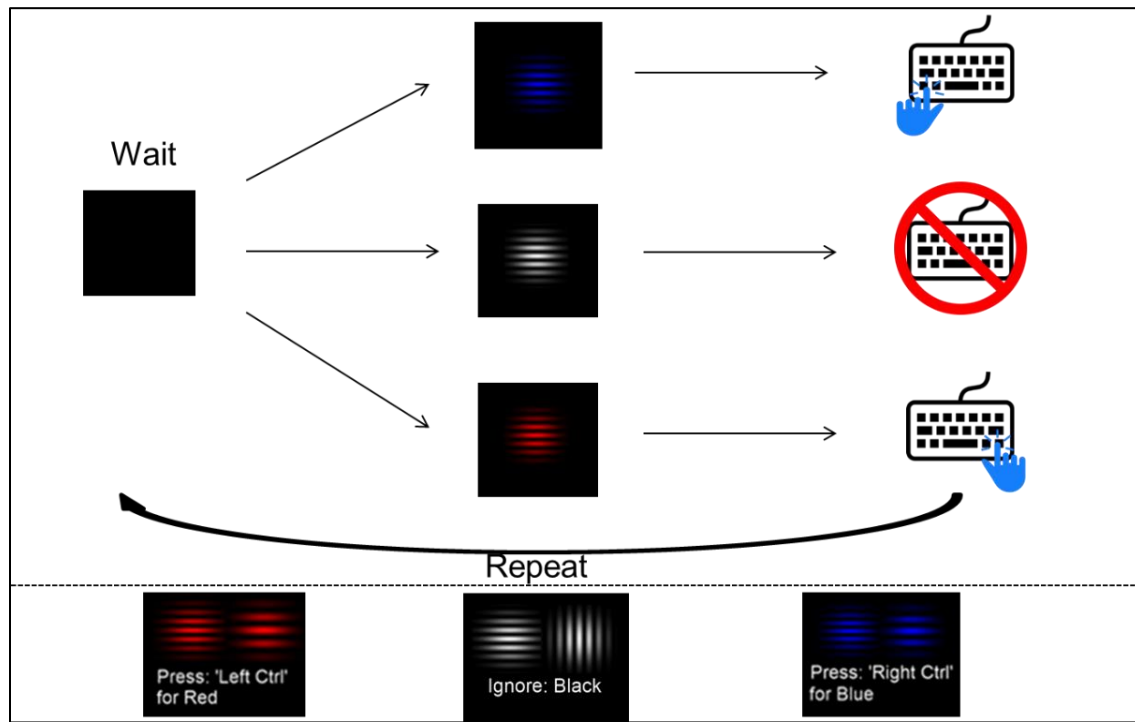


Figure 19: Go/No-Go Task

3.10.7. Measure 4 – Eriksen Flanker Task [27], [57], [65]

In the Eriksen Flanker task, the participant is presented with five arrows that are either all pointing in the same direction (congruent) or the center arrow is pointing in a direction opposite of the other arrows (incongruent). The arrow in the center is the target stimulus. The participant is asked to press an arrow key on the keyboard that indicates the direction of the target stimulus while ignoring the distractor, non-target stimuli.

The participant is presented with fixation crosshairs for 500 milliseconds followed by the flanker arrows for another 500 milliseconds. After the flanker arrows disappear from the screen, the crosshairs reappear and the computer waits for a response from the participant. After receiving the response, the screen goes blank for 1 second, and the

cycle repeats starting with another 500 milliseconds of fixation crosshairs. The entire process repeats 96 times and takes an average of 5 minutes to complete. The stimuli consist of even amounts of randomly-sequenced congruent/incongruent and left/right responses (i.e. 24 congruent-left, 24 congruent-right, 24 incongruent-left and 24 incongruent-right, appearing in random order). A graphical representation of this task can be seen in Figure 20.

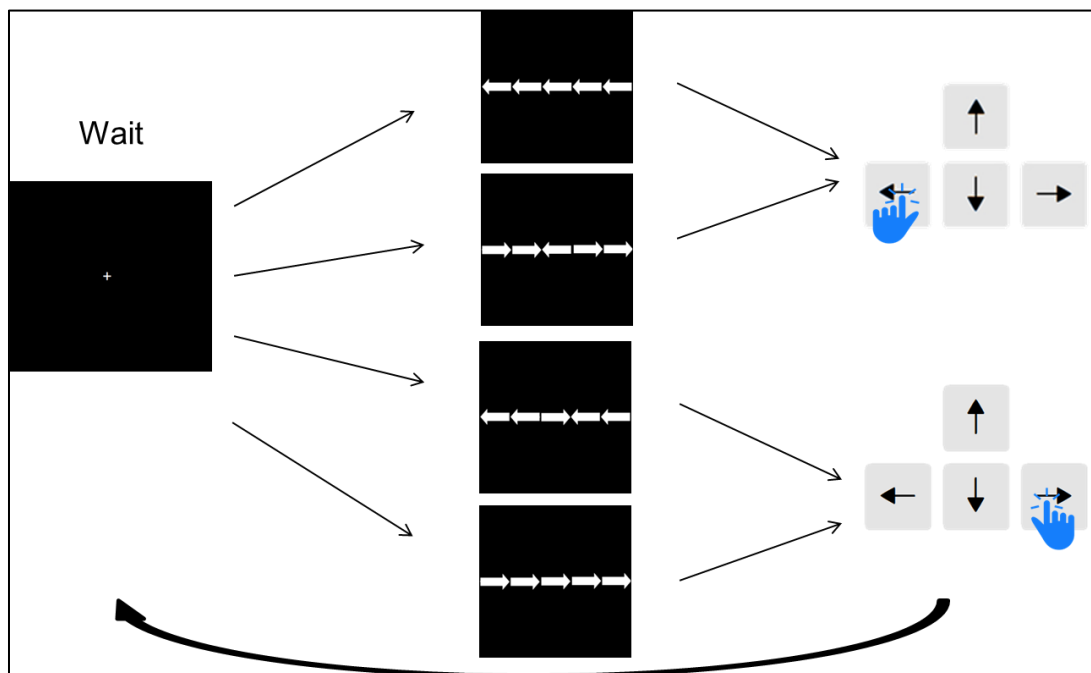


Figure 20: Eriksen Flanker Task

3.10.8. Measure 5 – N-back Task [65]

The goal of the n-back task is to measure working memory. In this task, letters are displayed one at a time on the screen. The participant must recall, and then compare the n^{th} -most recent letter shown to the letter currently displayed to determine if they are the same or not. The task is composed of two parts, the 2-back and the 3-back. The name of the task (2 or 3) represents how many letters the participant is required to remember at any given time. To perform the task, the participant is presented with a sequence of

uppercase letters, shown one letter at a time. Using the 2-back as an example, once the letter appears, the participant is asked to press the right control key if they saw the same letter exactly two iterations ago. If they did not see the current letter exactly two iterations ago, then they press the left control key. In the 3-back, the participant would look three iterations into the past instead of two. This is not timed, so the participant may use as much time as possible to answer, but is asked to do so as quickly as possible. Each portion shows 50 letters for a total of 100 letters shown between both parts. The stimuli were partitioned so that 60% of the letters were not seen n iterations previously, and 40% were seen n iterations previously. Figure 21 and Figure 22 show the steps to complete each task.

Additionally, it is important to note that during the 2-back, the first two letters can automatically be classified as “not the same” and during 3-back, the first three letters can automatically be classified as “not the same” since not enough letters have been seen up to that point to make a comparison. Therefore, those initial responses will need to be ignored during analysis.

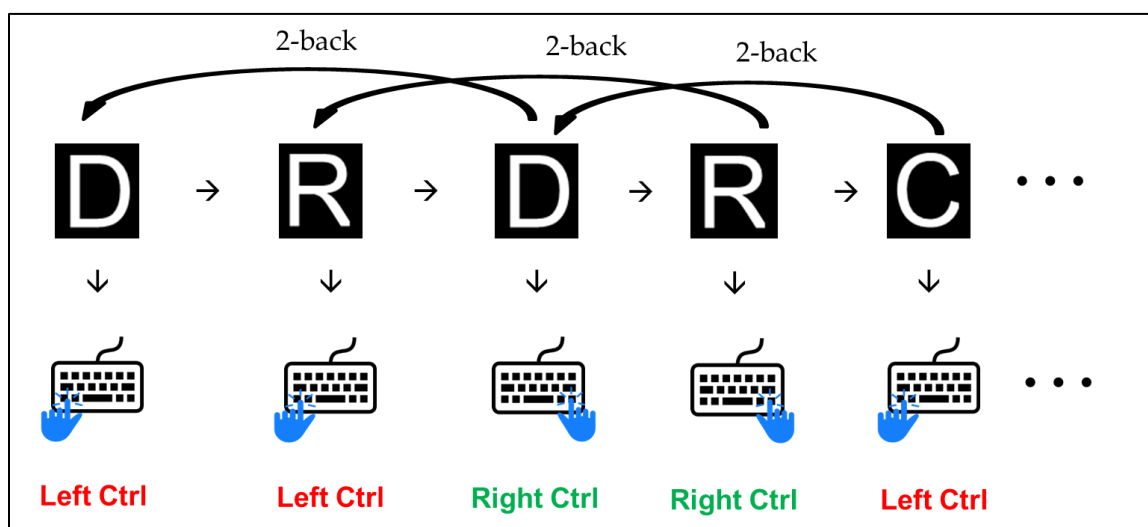


Figure 21: 2-Back Task

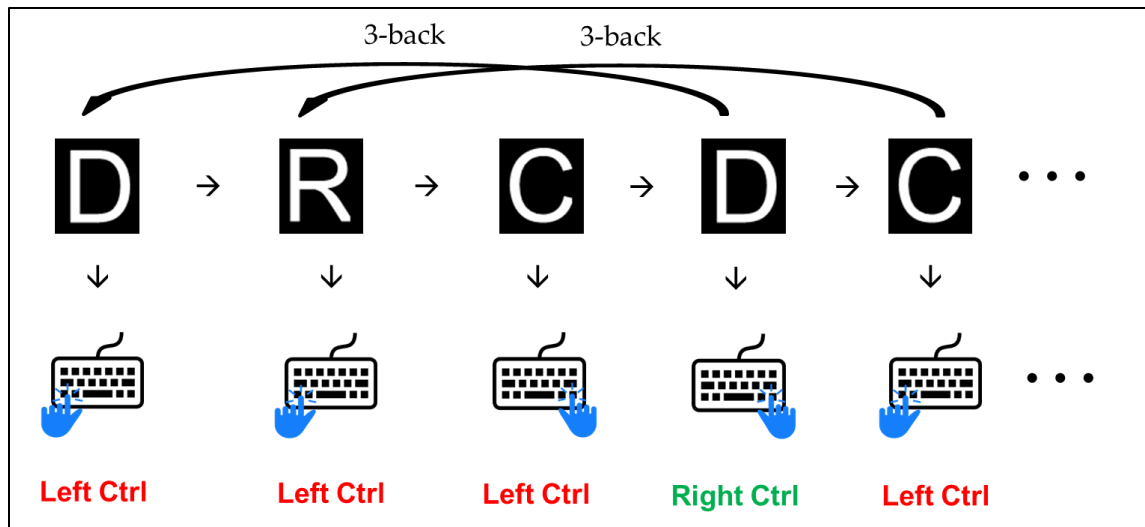


Figure 22: 3-Back Task

3.10.9. Measure 6 – Semantic Categorization Task [40]

The goal of the semantic categorization task is for the participant to categorize images as objects or animals. Objects consist of inanimate objects such as buildings, furniture, costumes, clothing, and animals are living creatures like dogs, cats, fish and birds. Plants and food items were not included to prevent confusion. The participants were presented with a subset of images from the Bank of Standardized Stimuli: Phase II [66]. There were a total of 120 images shown which were evenly split between objects and animals.

During the first 500 milliseconds, the participant is presented with a black screen with fixation crosshairs in the center. After 300 milliseconds have passed an image appears on the screen. At that point, the participant has two seconds to press the left control key if the image is of an object, or the right control key if the image is of an animal. If they do not classify the image within two seconds, the trial is automatically counted as incorrect. After two seconds have passed or they press one of the control keys,

a 1 second delay occurs and then the next image appears. A graphical representation of this task can be seen in Figure 23.

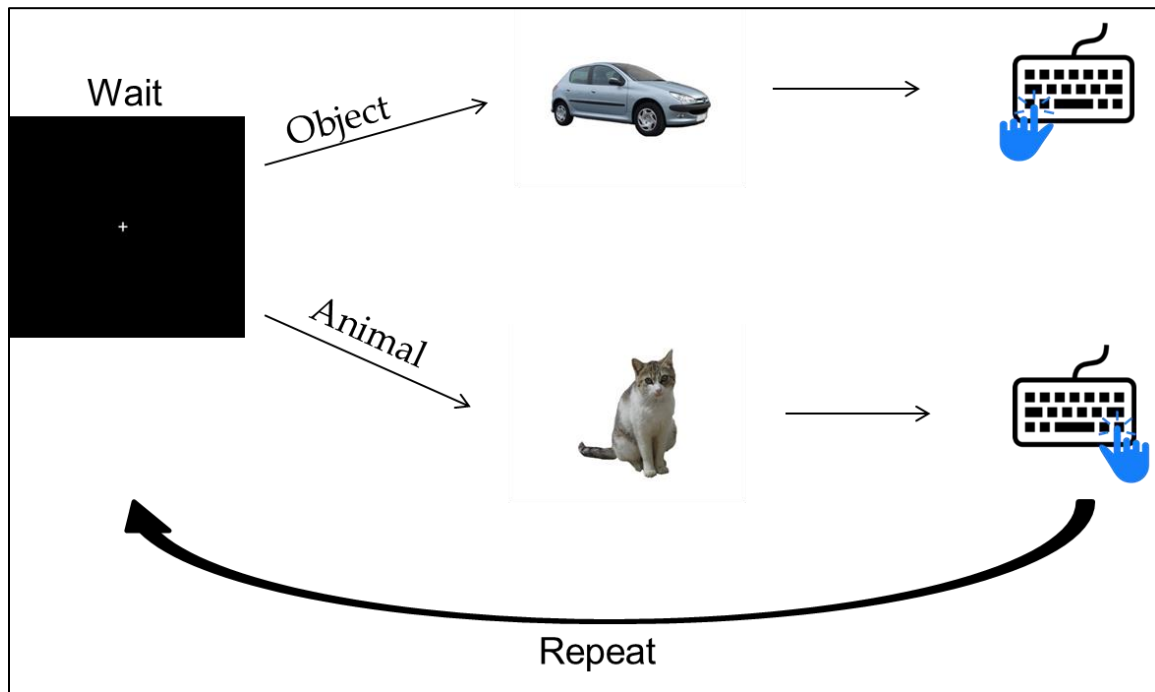


Figure 23: Semantic Categorization Task

3.10.10. Measure 7 – Stroop Task [35], [57], [59], [65]

In the Stroop task, the participant is presented with a sequence of names of colors, one at a time, in different colored fonts. The participant's task is to identify the font color while ignoring the color that the word spells. If the word is in red font, they press the left key, for green font, they press the down key, and for blue font, they press the right key. If the word and the font color match, the stimulus is congruent. If the font color and the word do not match, the stimulus is incongruent.

The participant starts with a blank screen for 500 milliseconds before the color word appears on the screen. The participant has an unlimited amount of time to indicate the font color. After the response there is a 1.5 second delay before the next letter appears. This process repeats 96 times with an equal number of congruent/incongruent

responses which are spread equally among the 3 colors (i.e. 48 congruent responses with 16 of each color, 48 incongruent responses with 8 of each color-word combination). A graphical representation of this task can be seen in Figure 24.

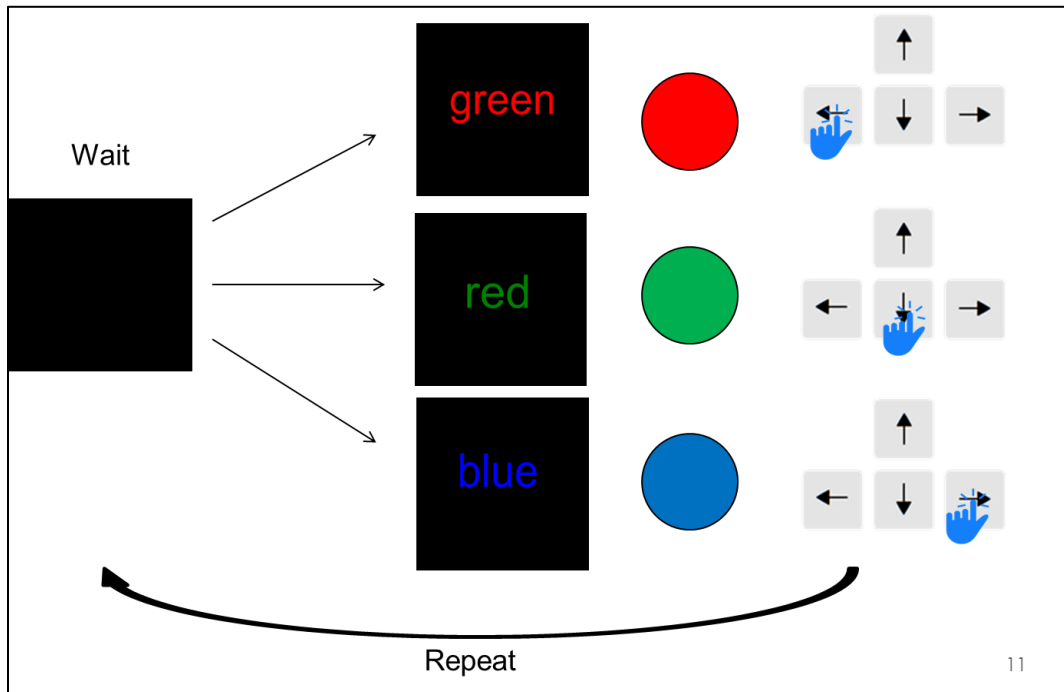


Figure 24: Stroop Task

3.11. Assumptions

While there is a large amount of literature on the effects of blue light, the results are surprisingly inconsistent. Due to the inconsistencies, various assumptions must be made.

- 1) Thirty minutes of treatment to blue or white light is enough time to induce an alerting effect. It has been shown that the alerting effects of blue light tend to taper off after a period of time. It was assumed that 30 minutes isn't long enough for the tapering to occur, but long enough for an effect of exposure to be seen in the experiment.

- 2) The participant has average levels of melatonin production, and there are no external factors affecting their alertness. While this study will do its best to determine if there are any external factors and consider them, it is possible for the individual to have unknown sleep abnormalities, stressors or other habits that affect alertness but are unknown to the participant.
- 3) The EEG, EOG, sleepiness scales and the participant's performance on cognitive tests are sufficient to detect the effects of blue and white light. White light is made up of a full spectrum of visible light (including blue). Due to this, the difference between the effects between blue and white light may be minimal. The selected tests should be challenging enough for the participant so that the differences in response time and accuracy should be apparent between the control and treatment.
- 4) 48 hours of wear of the activity/light band is enough to evaluate the participant's habits. It is possible that during the time the band is worn, the participant may partake in activities that are not normal indicators of their usual light/activity levels. It is assumed this is not the case
- 5) Since this is a within-participant design, each participant will experience both the treatment (blue light) and control (white light) pre-exposure conditions. Because participants could be better at the tasks in their second trial than they were in the first trial (learning effect), a counter-balanced experiment design was used. Some participants were given the blue light condition in the first trial and others experienced the white light condition in the first trial to reduce the impact of a learning effect in the

results. Additionally, two distinct (but equivalent difficulty) versions of the stimulus were created and used in the first and second trials to alleviate the concern that the participants could memorize the stimulus used in the first trial to perform better in the second trial.

- 6) There have been a few studies that have shown certain demographic features such as age, sex and certain types of recent food intake can affect the alerting effects of blue light. Since the evidence is sparse and inconclusive in this area, these considerations were recorded but not evaluated in this experiment.

3.12. Analysis Strategy

This section explains the analysis strategy used for each component of the experiment. Since data in this research was paired (i.e. all participants partook in both the blue and white conditions) and not normally distributed, the analysis relied heavily on the Wilcoxon Signed-Rank Test to determine the statistical significance much of the data. The Wilcoxon test uses the same type of analysis as the t-test, but uses the differences of the sums of the ranks of the population instead of comparing the means of the populations which allows it to be used for non-normally distributed populations. This specific version of the Wilcoxon test is used when comparing two related samples. Additionally, linear models were created from the cognitive test data and a Pearson Correlation was created from the data recorded from the activity band. The paragraphs below state when each method was used.

3.12.1. Stanford Sleepiness Scale

The participants were presented with the Stanford Sleepiness Scale a total of 7 times on each experiment day. Each answer reflects the participant's current feeling of alertness. Comparing the trend of alertness over time can show how quickly a participant's alertness wanes or increases. This analysis was done with the Wilcoxon Signed-Rank Test by comparing the answers provided by the same participant in each of the two lighting conditions. First, the compilation of all 7 scores for each participant/experiment day were compared. The combination should indicate the difference in the overall level of alertness between the blue and white exposure. Next, each iteration of the SSS was compared between the two experiment days to compare the levels of alertness at each point in the experiment. Finally, the first score was subtracted from the final score and then compared using the Wilcoxon test to determine the change in sleepiness in each lighting condition. After the analysis of the Wilcoxon test, the data was plotted over time to visually inspect the differences in responses. Cliff's Delta was used to determine effect size of the blue vs. white light. In order to produce effect size, Cliff's delta determines how often one value is larger than the other.

3.12.2. Cognitive Tasks

All cognitive tasks were analyzed using the recorded response time between stimulus presentation and participant response and the accuracy of task completion. The only exception to this was the RTT since it does not produce a number of correct responses due to the nature of the task (all responses are correct). Therefore, accuracy cannot be evaluated. Like the SSS, data from the cognitive tests was compared within participants for the blue and white conditions using the Wilcoxon test. Unlike SSS, it

compared accuracy, response time, response time of correct answers, response time of incorrect answers and cognitive throughput for each test individually and then all of the scores combined and a linear model was created in order to further evaluate the results.

In order to prepare data points to evaluate using the Wilcoxon Signed-Rank Test, two methods were used to parse and pair the data. In the first method, the average response time for each person per task were found. This resulted in 32 values per task (16 participants with both blue and white condition responses). Then, those 32 values were evaluated using the Wilcoxon Signed-Rank Test where each participant's average response time for the blue condition was paired with their response time for the white condition. This method was then repeated with accuracy, response time of correct answers and cognitive throughput.

The second method involved comparing individual responses between the blue and white conditions. This method was used to allow for more data points with the intent of providing a more accurate analysis. However, due to the independence assumption required to use the Wilcoxon Signed-Rank Test, the test could only be used to determine the effect the light had on each individual participant and not all of the participants combined.

To prepare the data for method two, each cognitive task needed to be evaluated differently since each participant took a different test version for each of the pre-exposure conditions. In the RTT, each stimulus had either a 1.5 second, 2.0 second or 2.5 second delay prior to being displayed. Data points were paired across the test versions/color condition according to delay time. Since it was time-based, participants didn't necessarily have the same number of responses between test versions. This resulted in extra stimuli

that could not be matched between the two versions. Therefore, those unmatched stimuli were dropped. The algorithm for how the matching occurred for the RTT is in Figure 25. The Go/No-Go task was the same between both versions of the test and individual response times could be paired, in order, between the two conditions. In the Eriksen Flanker task there were 16 possible images that were displayed 6 times each (congruent/incongruent, left/right pointing, 200/300/400/500 pixels in width). Each image was paired with one of its 5 other appearances in the test in temporal order. The Stroop task was compared similarly except it had 9 possible images with incongruent images repeated 8 times and congruent images repeated 16 times (red/green/blue, congruent/incongruent). The n-back and categorization tasks could only be matched based on two categories (same/different or object/animal). Since there were subjective differences in difficulty level between the stimuli within each of those categories, they were considered too dissimilar between the two versions of the test and therefore individual responses were not paired for the Wilcoxon analysis.

```

Assume all responses are temporally ordered in response time lists W (white trial) and B (blue trial)

For each participant:
  For delay d ∈ {1.5, 2.0, 2.5}:
    Select next w ∈ W with this d
    Select next b ∈ B with this d
    Create matched pair (w,b) and append to list L
    When either white or blue list is exhausted end FOR
  Compute the Wilcoxon signed rank test on L to test hypothesis
  Compute rank correlation on L to determine effect size
End FOR #participant

```

Figure 25: Response Time Pairing

To evaluate all of the participants together while also accounting for differences among stimuli, a third analysis method was used. In method three, a linear model was created. Instead of using the typical fixed effects linear model, a mixed effects linear

model was created. The benefit of a mixed effects linear model over a fixed effects model is that it is possible to account for differences within the data that can be caused by a group or categorical feature. The feature that is accounted for is called a random effect [67]. In the case of this research, a mixed effects model accounts for individual differences in a participant's baseline response time by creating a separate slope for each participant within the model. Therefore, participants that are naturally slower are weighted differently (have a different intercept) than participants who are naturally faster.

The resulting linear model can then be analyzed to determine the difference between blue and white lighting conditions. The coefficients of the linear model indicate the relationship between input variables and response time. In this particular linear model, all of the features are categorical which allow the coefficients to be on the same scale. One minor problem with using a linear model on the data in this experiment is that response time is inherently not normally distributed due to the physical limit in speed of human responses. Therefore, humans tend to try to respond as quickly as possible, skewing the response times to the right. Multiple transformations were tried in order to normalize the data, but none of them worked perfectly with the data. Fortunately, an ordinary least squares model can still be used as the best linear unbiased estimator per the Gauss–Markov theorem [68].

3.12.3. Questionnaire Answers

An important question when looking at lighting research is determining which, if any, habits, environmental factors, or demographics influence the non-visual effects of light. To further inspect environmental factors, a Pearson Product-Moment Correlation was performed. The Pearson Correlation measures the linear association between two

variables [69]. It produces values between -1 and 1 with high negative values indicating a large negative linear correlation and high positive values indicating a high positive correlation. Zero values indicate no correlation at all between the two variables. The guidelines for interpretation are listed in Table 9:

Table 9: Cohen's Effect Size Guidelines [70]

<i>Effect Size</i>	<i>Coefficient, r</i>	
	Positive	Negative
<i>Small</i>	0.1 to 0.3	-0.1 to -0.3
<i>Medium</i>	0.3 to 0.5	-0.3 to -0.5
<i>Large</i>	0.5 to 1.0	-0.5 to -1.0

Pearson Correlation was performed on the average amount of blue light a person is exposed to (in lux) based on the 48 hours of Actiwatch band recordings and their response time on the cognitive tests. The data was then plotted to view the linear relationship.

To better understand how demographics and habits are affected by a light treatment linear models were created from the response times. Unlike the analysis for the cognitive tests, the demographics analysis used fixed linear models to avoid collinearity between a feature inherent to the participant and the identification number of the participant themselves. The only demographic that was evaluated via a linear model was eye color. The original intent was to evaluate other demographics such as caffeine usage and age, but caffeine consumption was not measured precisely enough to analyze and there was not enough of a distribution in ages. However, eye color was distributed almost evenly with six individuals having blue eyes, four with brown, four with hazel, one with green and one individual refraining from answering. The unknown eye color was removed from the analysis.

3.13. Summary

This chapter discussed the methods used in this research to study the effects of the wavelength of visible light on human performance. To determine if different wavelengths of light have an effect, two versions of the experiment were completed with multi-spectrum (white) and 460 nm (blue) light. Additionally, since human performance is a vast area, this research focused on alertness and response time. These are explained in the response variable section. As outlined in Table 4, these variables can be measured via EEG, EOG, subjective testing, and cognitive testing. All of these measures were collected, but due to time constraints and complications with the EEG/EOG devices, only the subjective alertness tests and performance on cognitive measures were analyzed. The next chapter will discuss the results of this experiment.

IV. Analysis and Results

4.1. Chapter Overview

Various methods to record non-visual human reactions to light were used in this experiment. Electroencephalography (EEG) and electrooculography (EOG) were used as a non-subjective means to verify participant alertness. EEG was able to record brain signals to compare the results to potential patterns of drowsiness. EOG recorded eye movements to analyze the occurrence of slow eye movements (SEMs). The Stanford Sleepiness Scale (SSS) was used to get a subjective form of participant alertness. The six cognitive tasks were used to evaluate various forms of human cognition to find both alertness and cognitive improvement from response time and accuracy. Finally, demographics and the activity/light band helped to get a sense of participant's daily habits, activities and general light exposure. This chapter provides the results of the analysis of these measurements using the various statistical measurements that were outlined in the previous chapter.

4.2. Stanford Sleepiness Scale Results

The SSS was provided to the participant seven times throughout the experiment. They were asked to indicate their current level of alertness on a scale of 1 to 7 with a response of 1 being the most alert. Since a baseline SSS was not taken before the lighting exposure, no assumptions can be made on the initial alerting effects of the light, but instead this test was intended to determine how alertness changed over time based on the prior lighting exposure in order to answer the third research question: If there is a cognitive performance improvement induced by a pre-exposure to light, how quickly does it lessen over time?

Figure 26 shows all of the responses combined together. Since there were only seven responses to choose from, a swarm plot was drawn rather than a scatterplot to make it easier to see the distribution of values. It's difficult to pull any significant conclusions from this diagram, but this diagram makes it appear that the white condition had slightly fewer high numbered SSS scores (i.e. participants were less drowsy under the white condition). To further analyze the data, the mean was calculated on the combined data with the white condition's mean being 2.87 and the blue condition's mean being 2.89. The paired Wilcoxon test was performed on this data with a p-value of 0.65. This value implies a lack of statistical significance between the two conditions.



Figure 26: Combined SSS Scores

The next analysis technique that was performed on the SSS data used the same information on the previous diagram, but instead of comparing all of the data together, each iteration of the question was compared between the two conditions. Figure 27 shows

the median, maximum, minimum and interquartile range (IQR) responses per iteration. From the plot, it can be seen that the initial responses from the blue light condition start low (more alert), but they increase more rapidly than the white condition (drowsier). Since there were an even number of participants, four of the medians are not integers. Instead, they are represented by the mean of the two “middle” responses. Additionally, six of the white condition responses are considered outliers or suspected outliers. Outliers are defined as three times the size of IQR above/below the third/first quartile and suspected outliers are defined as 1.5 times the size of the IQR. This plot demonstrates a similar phenomenon as the previous plot. While the white condition responses start a bit higher on the scale there is only a small increase between the initial responses and the final responses. In the blue condition, the difference between the responses in the first iteration is significantly lower than the responses in the final iteration of the test.

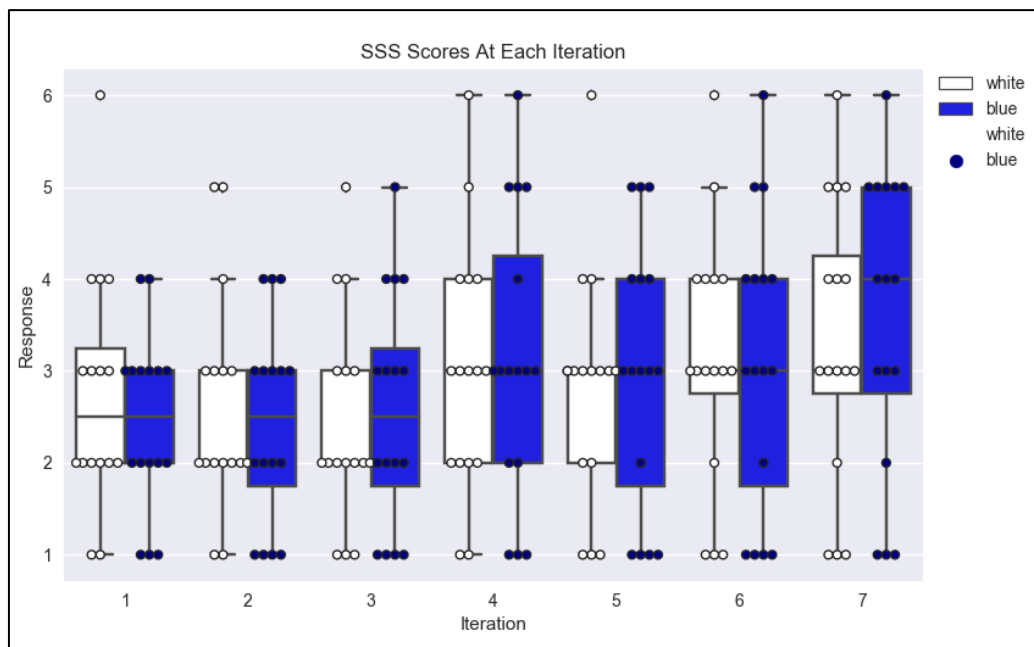


Figure 27: SSS Responses per Iteration - Boxplot

To determine if there was a statistical significance between the blue and white conditions at each iteration, a paired Wilcoxon test was done. In this analysis, the test compared only the responses from that particular iteration. However, none of the results show as statistically significant. The results of the Wilcox test are shown in Table 10.

Table 10: SSS Wilcoxon Test Results Per Iteration

Iteration	p-value
1	0.33
2	0.38
3	0.53
4	0.56
5	0.53
6	0.85
7	0.36

The final attempt at analysis on the SSS responses compared answers from the first iteration to the final iteration of the test to determine if there was a statistical difference between their answers. Figure 28 depicts this data visually. Negative numbers indicate that the participant's score went down between the first time the test was administered until the final time it was administered. For example, if a participant's initial response was 3, and their final response was 2, the difference would be labeled as -1 (more awake at the end by one point). From the diagram, it can be seen that four participants felt more awake at the end of the white condition while only two felt more awake at the end of the blue condition. To more accurately analyze the data, the mean and median were found. The white values had a mean of 0.56 and a median of 1.0. The blue values had a mean of 1.13 and a median of 1.0. These numbers indicate that both conditions caused the participants' drowsiness level to increase over time, but during the

white condition participants remained slightly more alert over time than when in the blue condition.

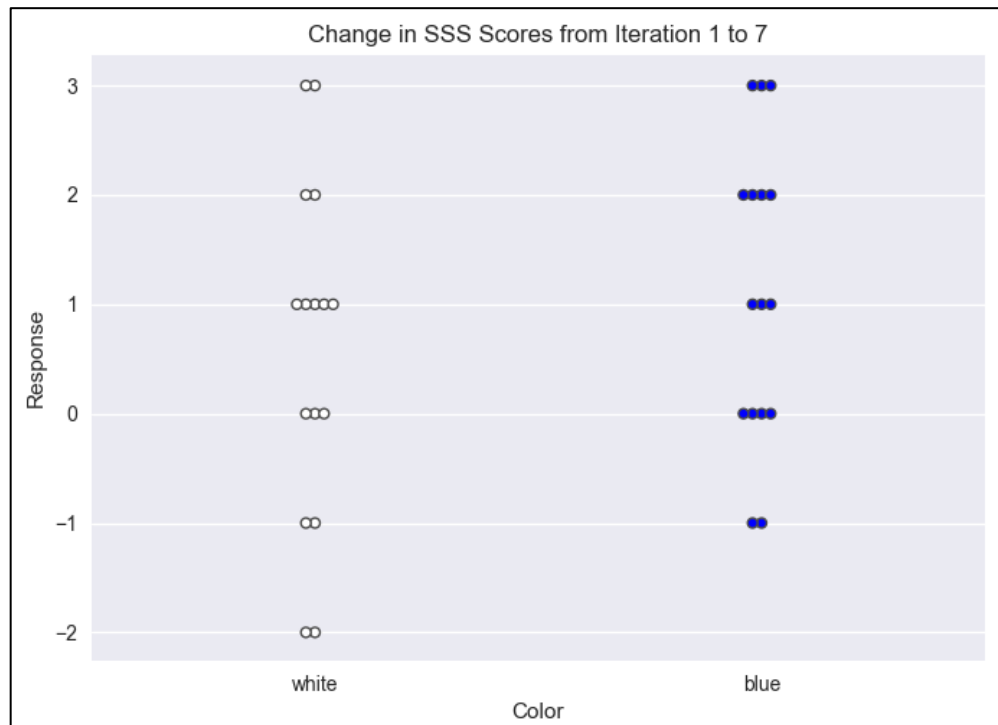


Figure 28: Change in SSS Scores Between First and Final Iteration

Since the chart, the mean, and the median are unable to compare each participant individually between both conditions, a Wilcoxon test was completed to see if there was a statistical significance between the changes. The p-value from the analysis was 0.14. Thus far, this is the lowest p-value, but it is still not less than the conventional 0.05. However, the number of data points in this analysis was small and a consideration can sometimes be made in these cases to raise the alpha required for the analysis to be considered statistically significant. Therefore, the results from the SSS do not clearly support the rejection of the null hypothesis, but there appears to be a smaller decrement in alertness under the white condition than the blue condition.

4.3. Cognitive Tests Results

There were six cognitive tests given after the 30-minute exposure period which intended to evaluate the effect of short-wavelength light exposure on various measures of human performance. Table 11 summarizes the six cognitive tasks in the order they were given to the participants, the cognitive function they intend to measure and the analysis techniques that were used on them.

Table 11: Analysis Techniques

Task	Cognitive Function	Analysis Technique
Reaction time	Response time	Average Response time (ms) (method 1) Individual Response Time (ms) (method 2) Linear Mixed Effects Model (method 3)
Go/No-Go	Response time Response Control	Average Response Time (ms) (method 1) Response Accuracy (%)
Eriksen Flanker	Selective Attention	Response time for Correct Answers (ms)
N-back	Working Memory	Response time for Incorrect Answers (ms)
Categorization	Semantic Memory	Cognitive Throughput (correct answers/sec)
Stroop	Working Memory Response Control	Individual Response Time (ms) (method 2) Linear Mixed Effects Model (method 3)

As mentioned in chapter 3, three methods of analysis were used to determine the effects of the pre-exposure to light. These three methods are specified in Table 11. Method one used response time averages and accuracy totals for each task and each participant. Then, a Wilcoxon Signed-Rank Test was performed on the data. This resulted in a total of 32 data points per task (one per participant per light color). Since the Wilcoxon test recommends a minimum of 20 data points, the minimum for the test was met, but the number of data points was still relatively low. Therefore, method two involved pairing individual responses between the two test versions. Since the tests weren't the same, the stimuli were not presented to the participant in the same order. To combat this problem, the individual responses were matched with stimuli that were the

same, but the matching stimulus was provided at a different point in the test. This resulted in nearly 100 data points per participant per exposure color (almost 3,200 total data points per test) and added a bit of granularity to the analysis. The final method of analysis involved the creation of a mixed linear effects model. This allowed each participant to be evaluated by a linear model that took into consideration individual differences between participants. The mixed linear effects model provided different slopes for each participant so that the differences could be seen more clearly.

In regards to method one, it is important to note that Response time for Correct Answers and Cognitive Throughput use similar data as Average Response time and Response Accuracy, but they tell slightly different stories. Response time for Correct Answers removes the potential slower response times that result in a participant being unsure of their answer. This measure demonstrates how fast the participant is able to do the things they are confident in. Cognitive Throughput, on the other hand, measures how many correct answers the participant can answer in one second. This measure only looks at the response time from the moment the stimulus is presented until the moment the participant responds and removes the delay time the test takes between stimuli. Looking at the responses with this method determines how often a participant picks the correct answer.

4.3.1. Average Response Time Analysis

The first analysis technique evaluated response time using method one. This technique was applied to all 6 cognitive tests (2-back and 3-back are separated in the analysis to make 7 total analyses). The response time for each test was averaged for each participant giving a total of 32 average response times (16 for the white condition and 16

for the blue condition) per test. A paired two-tailed Wilcoxon test was then run on these values to determine the statistical significance per test and all tests combined (224 total data points – 112 white and 112 blue). These data points can be seen in Table 28 (Appendix B). The Wilcoxon test was selected since the values were not normally distributed, and in the case of the combined test results, the data was very much skewed to the right.

The results from this analysis technique is shown in Table 12. The overall mean, standard deviation, maximum and minimum average response times are shown in the chart to give a general idea what the data looks like (they were not used in the Wilcoxon test). It is important to point out that these are based on average response times for the entire task per participant and not individual responses. Therefore, the min and max values are not overall min and max values, but instead the lowest and highest average response time among participants. The p-values, or difference between the mean ranks of the population, were determined by performing a paired Wilcoxon test on these values. As can be seen in the table, the only task that was able to individually reject the null hypothesis was the Go/No-Go task. However, it was in the opposite direction of the initial hypothesis. This implies that in response to the first research question (Table 2), there is not sufficient evidence to show that the blue light condition improved response time over the white light condition when evaluating response time.

Table 12: Response Time Analysis

Task:	White				Blue				p-val
	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	
<i>Reaction time</i>	353	46	462	290	356	35	438	312	0.76
<i>Go/No-Go</i>	581	53	670	486	607	72	780	509	0.02
<i>Flanker</i>	484	48	596	417	509	95	773	408	0.38
<i>2-Back</i>	1384	490	2750	766	1588	655	2834	687	0.08
<i>3-Back</i>	2107	949	4038	966	2341	1166	4800	863	0.06
<i>Categorization</i>	603	88	829	488	643	180	1223	492	0.72
<i>Stroop</i>	718	153	1099	505	795	242	1498	540	0.13

4.3.2. Response Accuracy Analysis

The next analysis technique looked at accuracy. Accuracy percentages for each participant were calculated for each test with the exception of the Reaction Time Task (RTT) since it does not provide data on correct vs incorrect responses. Then, a paired Wilcoxon test was performed using the 16 paired (32 total) accuracy percentages per participant/test. This was followed by a Wilcoxon test on all 96 paired (192 total) accuracy values. The results with the mean, min and max accuracy values can be seen in Table 13. As was expected, neither the white nor the blue lighting condition demonstrated a statistically significant improvement in any of the cognitive tests over the other. The null hypothesis could not be rejected in this case.

Table 13: Accuracy Analysis

Task:	White				Blue				p-val
	Mean (%)	STD (%)	Max (%)	Min (%)	Mean (%)	STD (%)	Max (%)	Min (%)	
<i>Reaction time</i>	***** No Accuracy Score *****								
<i>Go/No-Go</i>	97.39	2.19	100	92.31	96.43	5.46	100	76.92	0.64
<i>Flanker</i>	97.98	2.43	100	89.58	97.79	4.05	100	83.33	0.91
<i>2-Back</i>	91.84	20.32	100	14.29	95.03	7.6	100	71.43	0.72
<i>3-Back</i>	93.37	6.63	100	77.55	91.96	7.09	100	79.59	0.43
<i>Categorization</i>	97.29	1.73	100	95	94.95	11.03	100	52.5	0.97
<i>Stroop</i>	97.4	2.92	100	89.58	97.46	2.8	100	88.54	0.84

4.3.3. Response Time for Correct Answers

For the third analytical technique, the same evaluation that was done with average response time was done again, but this time just looking at the response time of correct responses. The data from this analysis is shown in Table 14. The results from this analysis nearly matched the response time analysis with only the Go/No-Go test resulting in a p-value below 0.05. The similarities between the two tests were to be expected due to the high levels of accuracy on these tests which caused almost all responses to be included in this analysis. Just like the response time analysis, response time for correct answers favored the white condition.

Table 14: Response time for Correct Answers Analysis

	White				Blue				
Task:	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	p-val
Response time	***** No Accuracy Score *****								
Go/No-Go	582	53	671	487	607	73.06	780	510	0.03
Flanker	481	45	565	418	493	62.9	669	408	0.44
2-Back	1413	512	2756	758	1573	660.49	2859	687	0.12
3-Back	2084	962	4038	939	2302	1170.2	4800	836	0.08
Categorization	599	87	829	489	596	94.92	826	469	0.72
Stroop	719	155	1107	506	787	219.62	1372	541	0.18

4.3.4. Response Time for Incorrect Answers

For the fourth technique, incorrect responses were evaluated. The results can be seen in Table 15. The intent with this evaluation was to determine if a pre-condition color caused the participants to perform better when making decisions they weren't certain about. Unfortunately, the number of possible data points was significantly smaller since it is not possible to compare the blue and white condition when a participant scored 100% on one of the two versions of the test. Additionally, it was not possible to create additional data points with analysis method two due to the independence assumption

required for the Wilcoxon Signed-Rank test. Using the available data points, the p-values were not small enough to produce any statistically significant data. However, the mean response time values from each condition clearly showed the white condition had faster response times when participants chose incorrect answers.

Table 15: Response time for Incorrect Answers Analysis

Task:	White				Blue				p-val
	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	Mean (ms)	STD (ms)	Max (ms)	Min (ms)	
<i>Response time</i>	*****No Accuracy Score*****								
<i>Go/No-Go</i>	550	130	884	425	581	67.08	684	484	0.28
<i>Flanker</i>	694	599	2142	350	1174	1662.76	5210	317	0.40
<i>2-Back</i>	1662	839	2973	634	2301	1839.23	6835	1030	0.40
<i>3-Back</i>	1944	728	3414	1050	2673	1808.06	7769	1224	0.15
<i>Categorization</i>	780	439	2000	417	865	419.22	1947	392	0.48
<i>Stroop</i>	706	228	1042	367	920	602.35	2472	400	0.51

4.3.5. Cognitive Throughput

The final analysis technique looked at cognitive throughput which is essentially the number of correct answers (or hits) per second. Similar to response time and response time for correct answers, Go/No-Go and the combined tests were the only statistically significant values found. Therefore, the null hypothesis can be rejected for those two measures in favor of the white condition. To answer the first research question, blue pre-

exposure does not provide improved cognitive effects over white light. The results of this analysis can be seen in Table 16.

Table 16: Cognitive Throughput Analysis

Task:	White				Blue				p-val
	Mean (hit/s)	STD (hit/s)	Max (hit/s)	Min (hit/s)	Mean (hit/s)	STD (hit/s)	Max (hit/s)	Min (hit/s)	
<i>Response time</i>	*****No Accuracy Score*****								
<i>Go/No-Go</i>	1.69	0.16	1.95	1.41	1.62	0.19	1.9	1.28	0.06
<i>Flanker</i>	2.04	0.21	2.37	1.64	1.98	0.33	2.4	1.24	0.33
<i>2-Back</i>	0.74	0.3	1.28	0.11	0.71	0.31	1.46	0.27	0.21
<i>3-Back</i>	0.53	0.21	0.94	0.25	0.5	0.24	1.09	0.21	0.15
<i>Categorization</i>	1.65	0.22	2.02	1.21	1.58	0.39	1.96	0.43	1.00
<i>Stroop</i>	1.41	0.28	1.96	0.85	1.32	0.34	1.83	0.59	0.18

4.3.6. Individual Response Time

In addition to matching response times overall, it's important to consider inter-participant differences as a large source of variance. Perhaps in some cases, individual participants preferred the blue pre-exposure over the white and vice versa. To do this analysis method two was used where responses were matched up individually between the two test versions. Each cognitive task had to be paired slightly differently since the two versions matched in slightly different ways for each test type. The n-back and categorization tasks were very dissimilar between the two versions due to the fact each test version used widely different variables (different sequences of letters and varying difficulty of image identification). To ensure no incorrect assumptions were made about the data, they were not used in the analysis. The other tasks allowed a direct matching across the two test versions.

In the RTT, each stimulus had either a 1.5, 2.0 or 2.5 second delay prior to being displayed. Data points were paired across the test versions according to delay time. A few

of the actual delay time matchings can be seen in Figure 29. The arrows indicate the responses that were paired.

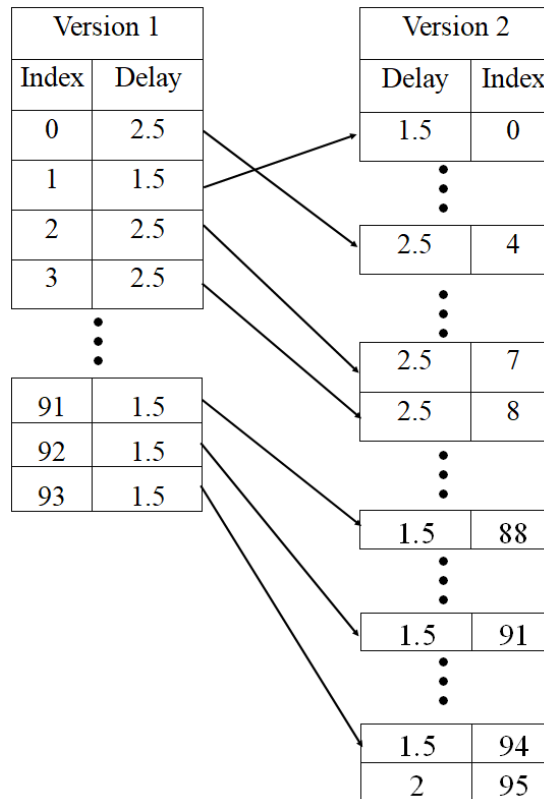


Figure 29: Delay Time Matching in Reaction Time Task

In the case of the Go/No-Go task, both versions of the test used the same order of stimuli. This was done since it was unlikely that participants would remember all four minutes of the tested pattern. In the event the participant was able to do this, the order in which the participants were exposed to the blue and white light was distributed evenly. Due to the fact the test was the same in both versions, responses were able to be matched exactly.

In the Eriksen Flanker task there were 16 possible arrow images that were displayed 6 times each (varying by arrow size and arrow direction). Each image was paired with one of its 5 other appearances in the test in temporal order. The Stroop task

was compared similarly except it had 9 possible stimuli (all combinations of red, green or blue font and written text) with incongruent stimuli repeated 8 times and congruent stimuli repeated 16 times.

In order to allow the Wilcoxon test to analyze non-normally distributed data, the test ranks the absolute value of the difference of each paired data point, but keeps track of the signed difference. The data below gives both the p-value, the t-statistic and the w-statistic. These extra Wilcoxon test statistics give more information than what was provided in sections 4.3.1 to 4.3.5. However, they were required for method two since the number of data points was much larger and individual data points could not be compared by hand to determine which pre-exposure condition performed better.

The t-statistic is the sum of the smallest of the signed ranks when taking the absolute value of the sum. The w-statistic is the sum of all of the signed ranks. In this case, the blue pre-condition response times were subtracted from the white response times. Therefore, a positive w-statistic would indicate that the blue pre-condition performed better (slower white response – faster blue response = positive difference), and a negative w-statistic would show that the white pre-condition performed better.

Additionally, the Wilcoxon rank correlation effect size (r) is reported. This is calculated by dividing the w-statistic by the total summed ranks ($r = \frac{w}{s}$) [71].

The data from this analysis is listed in Table 17 through Table 20. The first two columns are the participant's average response times for the task. These are for reference only. Individual responses were matched up before performing the Wilcoxon test, not the reported averages. Additionally, the number of paired responses where the blue pre-exposure condition performed better than the white condition was tallied. The “Percent of

Responses Faster w/ Blue” is the number of responses where blue was faster divided by the total number of responses $\left(\frac{\text{number of faster blue responses}}{\text{total number of responses}}\right)$. This was calculated to determine how often the blue condition performed better than the white condition for that participant. The final column uses the p-value and the w-statistic to determine which color improved performance for that participant.

Table 17: Inter-Participant Response Time Analysis - Reaction Time Task

<i>ID</i>	<i>Avg White RT (ms)</i>	<i>Avg Blue RT (ms)</i>	<i>t-stat</i>	<i>w-stat</i>	<i>Effect Size</i>	<i>p-value</i>	<i>Percent of Responses Faster w/ Blue</i>	<i>Color w/ Improved Performance</i>
1336	360	328	2154	63	0.014	0.904	49.46%	Neither
2339	350	386	1414	-1543	-0.353	0.003	36.56%	White
2436	298	322	1056	-2353	-0.527	9.14×10^{-06}	28.72%	White
2767	373	324	1096	2179	0.499	2.99×10^{-05}	72.04%	Blue
2861	381	369	1507	-1642	-0.353	0.003	30.21%	White
4836	314	382	1136.5	-2192	-0.491	3.58×10^{-05}	29.79%	White
5435	362	374	1458	-1455	-0.333	0.005	37.63%	White
6039	366	348	2005	361	0.083	0.489	53.76%	Neither
6208	327	312	1551	1363	0.305	0.010	60.64%	Blue
6336	351	338	1790	-885	-0.198	0.095	41.49%	Neither
6600	308	316	2020	-616	-0.132	0.260	47.92%	Neither
7211	441	438	1773	-640	-0.153	0.205	42.86%	Neither
7523	290	320	1844	-872	-0.191	0.106	40.00%	Neither
8828	326	391	1073	-2319	-0.519	1.23×10^{-05}	26.60%	White
9110	334	349	1733	905	0.207	0.083	53.76%	Neither
9672	462	391	1408	1370	0.327	0.007	60.44%	Blue

Table 18: Inter-Participant Response Time Analysis - Go/No-Go Task

<i>ID</i>	<i>Avg White RT (ms)</i>	<i>Avg Blue RT (ms)</i>	<i>t-stat</i>	<i>w-stat</i>	<i>Effect Size</i>	<i>p-value</i>	<i>Percent of Responses Faster w/ Blue</i>	<i>Color w/ Improved Performance</i>
1336	528	509	1158	610	0.208	2.15×10^{-04}	49.45%	Blue
2339	614	673	789	-1272	-0.446	2.45×10^{-07}	25.27%	White
2436	507	544	804	-1318	-0.450	3.37×10^{-07}	26.37%	White
2767	573	571	1396	-134	-0.046	0.006	37.36%	White
2861	571	547	1038	850	0.290	2.97×10^{-05}	50.55%	Blue
4836	486	572	612	-729	-0.373	4.58×10^{-09}	25.27%	White
5435	592	595	1199	-303	-0.112	4.03×10^{-04}	37.36%	White
6039	518	527	1273	-380	-0.130	0.001	35.16%	White
6208	602	601	1440	-46	-0.016	0.010	43.96%	White
6336	615	669	908	-1110	-0.379	2.73×10^{-06}	29.67%	White
6600	563	549	1267	392	0.134	0.001	47.25%	Blue
7211	660	672	1367	116	0.041	0.004	42.86%	Blue
7523	537	567	976	-974	-0.333	9.83×10^{-06}	34.07%	White
8828	670	780	295	-2336	-0.798	1.11×10^{-12}	13.19%	White
9110	621	679	675	-1576	-0.539	2.00×10^{-08}	24.18%	White
9672	636	663	941	-893	-0.322	5.13×10^{-06}	26.37%	White

Table 19: Inter-Participant Response Time Analysis - Flanker Task

<i>ID</i>	<i>Avg White RT (ms)</i>	<i>Avg Blue RT (ms)</i>	<i>t-stat</i>	<i>w-stat</i>	<i>Effect Size</i>	<i>p-value</i>	<i>Percent of Responses Faster w/ Blue</i>	<i>Color w/ Improved Performance</i>
1336	417	408	1673	1310	0.281	0.017	67.71%	Blue
2339	456	471	2059	-538	-0.116	0.326	43.75%	Neither
2436	439	451	1777	-1102	-0.237	0.044	41.67%	White
2767	444	448	2153	-350	-0.075	0.522	47.92%	Neither
2861	475	457	2224	208	0.045	0.704	45.83%	Neither
4836	463	626	1836	-984	-0.211	0.072	39.58%	Neither
5435	542	467	2055	546	0.117	0.318	58.33%	Neither
6039	487	470	1584	1488	0.320	0.007	62.50%	Blue
6208	471	495	1429	-1798	-0.386	0.001	37.50%	White
6336	454	462	1885	-886	-0.190	0.105	42.71%	Neither
6600	449	433	1630	1396	0.300	0.011	58.33%	Blue
7211	527	507	1712	1232	0.265	0.024	65.63%	Blue
7523	456	461	1652	-1352	-0.290	0.013	38.54%	White
8828	567	669	414	-3828	-0.822	2.66×10^{-12}	21.88%	White
9110	502	548	1305	-2046	-0.439	1.85×10^{-04}	34.38%	White
9672	596	773	2037	-582	-0.125	0.288	47.92%	Neither

Table 20: Inter-Participant Response Time Analysis - Stroop Task

<i>ID</i>	<i>Avg White RT (ms)</i>	<i>Avg Blue RT (ms)</i>	<i>t-stat</i>	<i>w-stat</i>	<i>Effect Size</i>	<i>p-value</i>	<i>Percent of Responses Faster w/ Blue</i>	<i>Color w/ Improved Performance</i>
1336	537	540	2212	232	0.050	0.672	57.29%	Neither
2339	721	835	1574	-1508	-0.324	0.006	33.33%	White
2436	505	562	1739	-1178	-0.253	0.031	42.71%	White
2767	591	553	1738	1180	0.253	0.031	57.29%	Blue
2861	876	972	1669	-1318	-0.283	0.016	36.46%	White
4836	607	1498	931	-2794	-0.600	3.31×10^{-07}	27.08%	White
5435	862	676	1097	2462	0.529	6.84×10^{-06}	73.96%	Blue
6039	621	664	1970	-716	-0.154	0.191	47.92%	Neither
6208	639	639	2144	368	0.079	0.501	52.08%	Neither
6336	605	666	1424	-1808	-0.388	0.001	31.25%	White
6600	699	625	1677	1302	0.280	0.017	64.58%	Blue
7211	924	821	1851	954	0.205	0.081	57.29%	Neither
7523	682	742	1654	-1348	-0.290	0.014	32.29%	White
8828	773	970	794	-3068	-0.659	2.07×10^{-08}	18.75%	White
9110	748	859	1670	-1316	-0.283	0.016	36.46%	White
9672	1099	1100	1742	-1172	-0.252	0.032	44.79%	White

As can be seen from the table, there was an obvious improvement in the white condition among all participants for the Go/No-Go task. However, it's somewhat difficult in this format to determine if there were any participants that tended to perform better under one condition than the other. To consolidate the information on the participants, Table 21 shows the count per test of where the improvement was seen for each color pre-exposure condition.

As can be seen in Table 21, there were two participants with a clear improvement during the white condition, four others that performed mostly better (3 out of 4) under the white condition and one that was somewhat better under the blue condition (3 out of 4). The rest were evenly dispersed in which condition showed a majority of their improvements. Overall, most of the performance improvements were found in the white condition followed by neither condition causing an improvement over the other.

Table 21: Individual Response Participant Improvement Count

<i>participant</i>	<i>Better Blue Performance</i>	<i>Better White Performance</i>	<i>Neither Improvement</i>
1336	2	0	2
2339	0	3	1
2436	0	4	0
2767	2	1	1
2861	1	2	1
4836	0	3	1
5435	1	2	1
6039	1	1	2
6208	1	2	1
6336	0	2	2
6600	3	0	1
7211	2	0	2
7523	0	3	1
8828	0	4	0
9110	0	3	1
9672	1	2	1
Total	14	32	18

4.3.7. Mixed Effects Linear Model

While a Wilcoxon Signed-Rank test is a good analysis technique to determine if there was a performance improvement between two conditions, it tends to leave out some interactions among other features of the experiment. This is where a linear model can provide more insight into what is actually occurring in the data. Essentially, a model is created from the data that provides a method to predict future outcomes and allows a comparison of the coefficients of each feature. Most commonly, a fixed effect model is used to analyze data, but fixed effects do not allow the model to account for “baseline” individual differences among the different features. In the case of this experiment, it would prevent the fixed effects model from taking into account the fact that each participant may have had a different baseline response time. Conversely, a Mixed Effects

Linear model allows a researcher to evaluate information that is known to cause an offset (like a participant's normal response time) by modeling these random effects.

Table 22 shows the data collected from the model. The model was created using the function MixedLM from the Python package statsmodels. This function allows the specification of random and fixed effects and then fits a model. It's important to note that while the fixed effects report the coefficients for the model, the random effects report the variance explained by each random effect in the model. To help get a perspective on how much variance the random effect explains in the model, the percentage of the random effects variance to the total variance in the test is shown in the results. As can be seen in Table 22, less than half of the variance is explained by the participant with the exception of the Flanker task. In the flanker task, a vast majority of the variance is due to the participant (almost 94%).

Since all of the fixed effects in this model were categorical variables, their values are represented by a 0 or 1 in the model. For this reason, categorical items not shown in the chart are represented by a 0 and explained by intercept. For example, in the case of the RTT, the model would use a 1 to model that the white pre-condition was in effect for the observation and 0 for blue. Therefore, a negative number in "C(Color)[T.white]" implies that the difference in milliseconds to get from the blue condition to the white condition (while considering the other fixed effects) is negative (i.e. participants performed faster under the white condition). Another factor that can be considered in this model is the different types features of the tasks and how the participant responded. In, the RTT, the same evaluation technique could be applied to the delay indicating that

participants were fastest with 2.0 second delays, followed by 1.5 second delays (explained by the intercept) and then 2.5 second delays.

Table 22: Mixed Effects Linear Model

Tasks	Features	Coef.	Std.Err.	z	P> z	Variance	% of total Variance
Reaction Time	<i>Intercept</i>	361.251	11.124	32.476	0.000		
	<i>C(Color)[T.white]</i>	-3.021	6.941	-0.435	0.663		
	<i>C(StimDelay)[T.2.0]</i>	-18.288	8.383	-2.182	0.029		
	<i>C(StimDelay)[T.2.5]</i>	2.166	8.592	0.252	0.801		
	<i>Participant (RE)</i>					1217.3	3.24%
Go/No Go	<i>Intercept</i>	596.961	22.934	26.030	0.000		
	<i>C(Color)[T.white]</i>	-26.473	5.058	-5.234	0.000		
	<i>C(Correct)[T.True]</i>	7.364	16.829	0.438	0.662		
	<i>C(stim)[T.Red]</i>	10.268	5.064	2.028	0.043		
	<i>C(stimLoc)[T.Right]</i>	-3.997	5.202	-0.768	0.442		
	<i>Participant (RE)</i>					3803.0	19.85%
Flanker	<i>Intercept</i>	961.604	102.460	9.385	0.000		
	<i>C(Color)[T.white]</i>	-24.134	13.160	-1.834	0.067		
	<i>C(Correct)[T.True]</i>	-441.655	47.097	-9.378	0.000		
	<i>C(Congruency)[T.True]</i>	-41.402	13.239	-3.127	0.002		
	<i>Participant (RE)</i>					133008.1	93.55%
2-Back	<i>Intercept</i>	2074.818	174.123	11.916	0.000		
	<i>C(Color)[T.white]</i>	-217.287	45.541	-4.771	0.000		
	<i>C(Correct)[T.True]</i>	-405.850	102.973	-3.941	0.000		
	<i>C(corrAns)[T.Same]</i>	-248.088	46.221	-5.367	0.000		
	<i>Participant (RE)</i>					308331.7	27.50%
3-Back	<i>Intercept</i>	2932.352	301.210	9.735	0.000		
	<i>C(Color)[T.white]</i>	-227.247	65.175	-3.487	0.000		
	<i>C(Correct)[T.True]</i>	-452.996	128.625	-3.522	0.000		
	<i>C(corrAns)[T.Same]</i>	-428.705	66.426	-6.454	0.000		
	<i>Participant (RE)</i>					1175192.1	42.00%
Categorization	<i>Intercept</i>	1190.794	29.761	40.012	0.000		
	<i>C(Color)[T.white]</i>	-25.920	5.826	-4.449	0.000		
	<i>C(Correct)[T.True]</i>	-601.386	15.832	-37.985	0.000		
	<i>C(corrAns)[T.Object]</i>	46.305	5.818	7.959	0.000		
	<i>Participant (RE)</i>					10203.2	17.59%
Stroop	<i>Intercept</i>	989.825	66.097	14.975	0.000		
	<i>C(Color)[T.white]</i>	-77.161	15.470	-4.988	0.000		
	<i>C(Correct)[T.True]</i>	-108.473	49.796	-2.178	0.029		
	<i>C(congruent)[T.True]</i>	-103.175	15.516	-6.650	0.000		
	<i>C(corrAns)[T.left]</i>	-75.215	18.955	-3.968	0.000		
	<i>C(corrAns)[T.right]</i>	-36.818	18.949	-1.943	0.052		
	<i>Participant (RE)</i>					28480.2	13.19%

The z value in the results is the coefficient divided by the standard error. The hope is to have a small standard error that is at least 4 or 5 times less than the coefficient. The z value indicates how much smaller/larger the standard error actually is. Therefore, the larger the z value, the smaller the $P > |z|$ value. This is an indication of how accurately that particular coefficient explains the data.

As can be seen from the data, when accounting for differences among stimuli in the test, the white condition always produces faster estimated response times than the blue condition. However, the RTT and Flanker task did not produce statistically significant data (i.e. the standard error was too large). The response time improvement with the white light pre-exposure is most apparent in the 2-back and 3-back tests where participants are required to make a decision instead of a simple reaction. As was expected based on current literature, the Flanker and Stroop showed that congruent response times are generally faster. In all of the tests where accuracy is a consideration (i.e. $C(\text{Correct})[T.\text{True}]$), as expected, participants performed significantly faster when they knew the answer. The exception to this was the Go/No-Go task, but the “Correctness” variable had too large of a standard error for the model to be certain of the result. During the n -back tasks, participants performed faster when the stimulus was the “same” stimulus n stimuli ago rather than a different stimulus. During the Stroop task, participants performed fastest when the stimulus was ‘red’ (or left arrow key) and ‘blue’ (right arrow key) than they did for ‘green’ (down arrow key).

While looking at each feature individually can give a lot of information, it is also important to look at interaction effects. A second mixed linear model was created to evaluate how white light interacted with various features of the test and participant

performance. The results from this model can be seen in Table 23. Similar to the mixed effects model without the interaction terms, variance based on the participant was relatively low with the exception of the Flanker test. The white pre-exposure condition continued to result in lower reaction times than the blue pre-exposure condition with the exception of the reaction time test. However, the standard error was much higher than the coefficient resulting in a p -value of 0.914. Additionally, under the white condition and a stimulus delay of 2.0 seconds or 2.5 seconds, the resulting estimated response time continues to be less than the blue condition with the same delays (white/2.0 = 336.5, blue/2.0 = 346.4, white/2.5 = 361.9, blue/2.5 = 362.0).

It is also interesting to note that in all tasks, the interaction effect under the white condition with a correct answer (C(Color)[T.white]:C(Correct)[T.True]) was positive. This implies that while participants performed better when they knew the answer under both the blue and white conditions (C(Correct)[T.True]), the difference in response time between knowing and not knowing the answer under the white condition was lessened. An example of this can be seen in the 2-back task. The model for that task is the following:

$$2226.072 - 483.326x_1 - 563.308x_2 - 252.077x_3 + 284.219x_1x_2 \quad (4)$$

Where:

x_1 = Color (white = 1, blue = 0)

x_2 = Correctness (correct = 1, incorrect = 0)

x_3 = Was the stimulus the same two iterations ago? (True = 1, False = 0)

Holding the variable “corrAns” or x_3 (the correct answer for that stimulus) constant as zero (the stimulus was different than the stimulus seen two iterations ago), the white condition estimates a response time of 1463.7 ms for correct answers and 1742.7

ms for incorrect answers. The difference between correct and incorrect is 279.0 ms. For the blue condition, the estimated response time for correct answers is 1662.8 ms and incorrect answers is 2226.1 ms. The difference between correct and incorrect in the case of the blue pre-exposure is 563.3 ms. This same pattern occurs in all of the choice reaction time tasks in this experiment with the individual “correctness” variable and the individual pre-exposure variable being negative and the interaction between the two being positive (i.e. the model lessens the effect of not knowing answer under the white condition). However, only the *p*-values in the Flanker (selective attention), Categorization (semantic memory) and Stroop (response control and working memory) tasks can be considered statistically significant. The *p*-values in the Go/No-Go (response time and response control), 2-back (working memory) and 3-back (working memory) tasks were above 0.05.

Table 23: Mixed Effects Linear Model with Interaction Effects

Tasks	Features	Coef.	Std.Err.	z	P> z	Variance	% of total
Reaction Time	<i>Intercept</i>	359.084	12.132	29.599	0.000		
	<i>C(Color)[T.white]</i>	1.292	11.949	0.108	0.914		
	<i>C(StimDelay)[T.2.0]</i>	-12.680	11.901	-1.065	0.287		
	<i>C(StimDelay)[T.2.5]</i>	2.869	12.169	0.236	0.814		
	<i>C(Color)[T.white]:C(StimDelay)[T.2.0]</i>	-11.181	16.836	-0.664	0.507		
	<i>C(Color)[T.white]:C(StimDelay)[T.2.5]</i>	-1.386	17.207	-0.081	0.936		
	<i>Participant (RE)</i>					1210.387	3.22%
Go/No Go	<i>Intercept</i>	623.712	28.694	21.737	0.000		
	<i>C(Color)[T.white]</i>	-77.197	33.091	-2.333	0.020		
	<i>C(Correct)[T.True]</i>	-20.096	24.422	-0.823	0.411		
	<i>C(stim)[T.Red]</i>	10.355	5.063	2.045	0.041		
	<i>C(stimLoc)[T.Right]</i>	-3.896	5.201	-0.749	0.454		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	51.959	33.498	1.551	0.121		
	<i>Participant (RE)</i>					3805.198	19.86%
Flanker	<i>Intercept</i>	1261.385	110.390	11.427	0.000		
	<i>C(Color)[T.white]</i>	-644.143	90.231	-7.139	0.000		
	<i>C(Correct)[T.True]</i>	-757.039	64.503	-11.74	0.000		
	<i>C(Congruency)[T.True]</i>	-24.157	18.615	-1.298	0.194		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	649.358	91.651	7.085	0.000		
	<i>C(Color)[T.white]:C(Congruency)[T.True]</i>	-31.254	26.269	-1.190	0.234		
	<i>Participant (RE)</i>					130942.711	92.10%
2-Back	<i>Intercept</i>	2226.072	204.606	10.880	0.000		
	<i>C(Color)[T.white]</i>	-483.326	195.714	-2.470	0.014		
	<i>C(Correct)[T.True]</i>	-563.308	152.605	-3.691	0.000		
	<i>C(corrAns)[T.Same]</i>	-252.077	46.297	-5.445	0.000		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	284.219	203.352	1.398	0.162		
	<i>Participant (RE)</i>					305781.922	27.28%
3-Back	<i>Intercept</i>	2982.076	319.544	9.332	0.000		
	<i>C(Color)[T.white]</i>	-336.718	243.801	-1.381	0.167		
	<i>C(Correct)[T.True]</i>	-506.765	172.826	-2.932	0.003		
	<i>C(corrAns)[T.Same]</i>	-429.382	66.459	-6.461	0.000		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	118.056	253.346	0.466	0.641		
	<i>Participant (RE)</i>					1174938.954	41.99%
Categorization	<i>Intercept</i>	1453.278	30.162	48.182	0.000		
	<i>C(Color)[T.white]</i>	-719.712	29.480	-24.41	0.000		
	<i>C(Correct)[T.True]</i>	-877.114	18.727	-46.84	0.000		
	<i>C(corrAns)[T.Object]</i>	44.935	5.427	8.279	0.000		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	719.747	30.058	23.945	0.000		
	<i>Participant (RE)</i>					9180.733	15.83%
Stroop	<i>Intercept</i>	1233.884	81.483	15.143	0.000		
	<i>C(Color)[T.white]</i>	-559.288	96.617	-5.789	0.000		
	<i>C(Correct)[T.True]</i>	-360.017	70.103	-5.136	0.000		
	<i>C(congruent)[T.True]</i>	-101.149	21.862	-4.627	0.000		
	<i>C(corrAns)[T.left]</i>	-74.693	18.883	-3.956	0.000		
	<i>C(corrAns)[T.right]</i>	-37.082	18.877	-1.964	0.049		
	<i>C(Color)[T.white]:C(Correct)[T.True]</i>	496.685	97.821	5.077	0.000		
	<i>C(Color)[T.white]:C(congruent)[T.True]</i>	-3.575	30.911	-0.116	0.908		
	<i>Participant (RE)</i>					27878.099	12.91%

4.4. Demographics and Habits Results

Various demographics, habits and current activities of the participants were recorded for later evaluation. This section demonstrates their potential effect on the participants and how they reacted to the light treatment.

4.4.1. Daily Blue Light Exposure

Very few studies have attempted to look at how the amount of light a person receives regularly throughout their daily activities affects how much a person will be affected by a light treatment (irrespective of color/wavelength). The participants in this study wore a light-monitoring band for 48 hours prior to the experiment. This provides a rough estimate to the amount of light they receive on a regular basis. The output from the band provided light levels for each main color band (red, green and blue) in lux at 30-second epochs. It averaged these 30-second epochs during the wear period to provide the typical amount of blue light (in lux) each participant was exposed to over the wear period. The average blue light measurements recorded by the band are listed in Table 24.

Table 24: Daily Blue Light Exposure Averages

<i>Measurement</i>	<i>Exposure (lux)</i>
<i>Average</i>	79.16
<i>Standard Deviation</i>	47.86
<i>Maximum Average</i>	202.0
<i>Minimum Average</i>	22.9

It is important to realize that this band is kept on the participant's wrist and not at eye level. Participants were instructed to prevent the band from being covered as much as possible, but even with those instructions it is still not possible to collect the exact amount of light reaching the eye at any given moment. However, the measurement

location, the wrist, remained the same among participants. Future work in this area should look at the effects of light while measuring light intake at eye level.

To compare the association between the average blue light a person receives to how that affects a light treatment, a Pearson Correlation was performed on the participant's average response time for each test and the typical amount of blue light they are exposed to. The Pearson Correlation provides an r -value between -1 and 1 to indicate if the data is positively or negatively associated with each other. A zero value indicates no association. A p -value greater than 0.5 or less than -0.5 has a high association. A p -value between 0.3 to 0.5 or -0.3 to -0.5 to has a medium association.

Each pre-exposure condition was evaluated individually and then the difference between white and blue were analyzed (white response time – blue response time). Since the blue pre-condition response times were subtracted from the white condition, a positive r -value indicates a positive correlation between average daily blue light and the white pre-exposure response time compared to blue (increased average daily blue light correlates to slower response time). A negative r -value would indicate faster response times in the white pre-exposure condition compared to the blue pre-exposure condition per each increase in daily blue light. The values collected are listed in Table 25.

Table 25: Pearson Correlation of Avg Daily Blue Light Exposure to Response Time

Task:	White		Blue		White - Blue	
	r -value	p -value	r -value	p -value	r -value	p -value
Reaction time	0.61	0.01	0.16	0.55	0.61	0.01
Go/No-Go	0.26	0.32	0.04	0.89	0.30	0.25
Flanker	0.4	0.12	0.36	0.17	-0.23	0.39
2-Back	0.39	0.13	0.41	0.12	-0.17	0.52
3-Back	0.29	0.27	0.20	0.45	0.10	0.72
Categorization	0.39	0.13	0.09	0.74	0.11	0.68
Stroop	0.57	0.02	0.14	0.60	0.23	0.39

As can be seen from the table, when looking at the white light pre-exposure condition individually, all tests except Go/No-Go have a medium to high positive association. A positive association implies that the more blue light a person receives on a daily basis, the slower their response time. In other words, an increase in blue light tends to reduce the positive response time effects of the white light treatment. However, there seems to be a much smaller association between response time after a blue light treatment and daily blue light exposure. This is likely because the blue light condition was not shown to have as much of an effect on response time. As for average daily blue light having an effect on the improvement with the pre-exposure conditions, the only two tasks with a medium to high correlation are the RTT and Go/No-Go. They are both correlated to an increase in response time (slower) in the white condition with each increase in average daily blue light exposure.

Figure 30 gives a visual representation of this data. The lines on the graphs represent a linear fit and the shaded areas represent the 95% confidence interval. The greater the slope of the line, the greater the correlation.

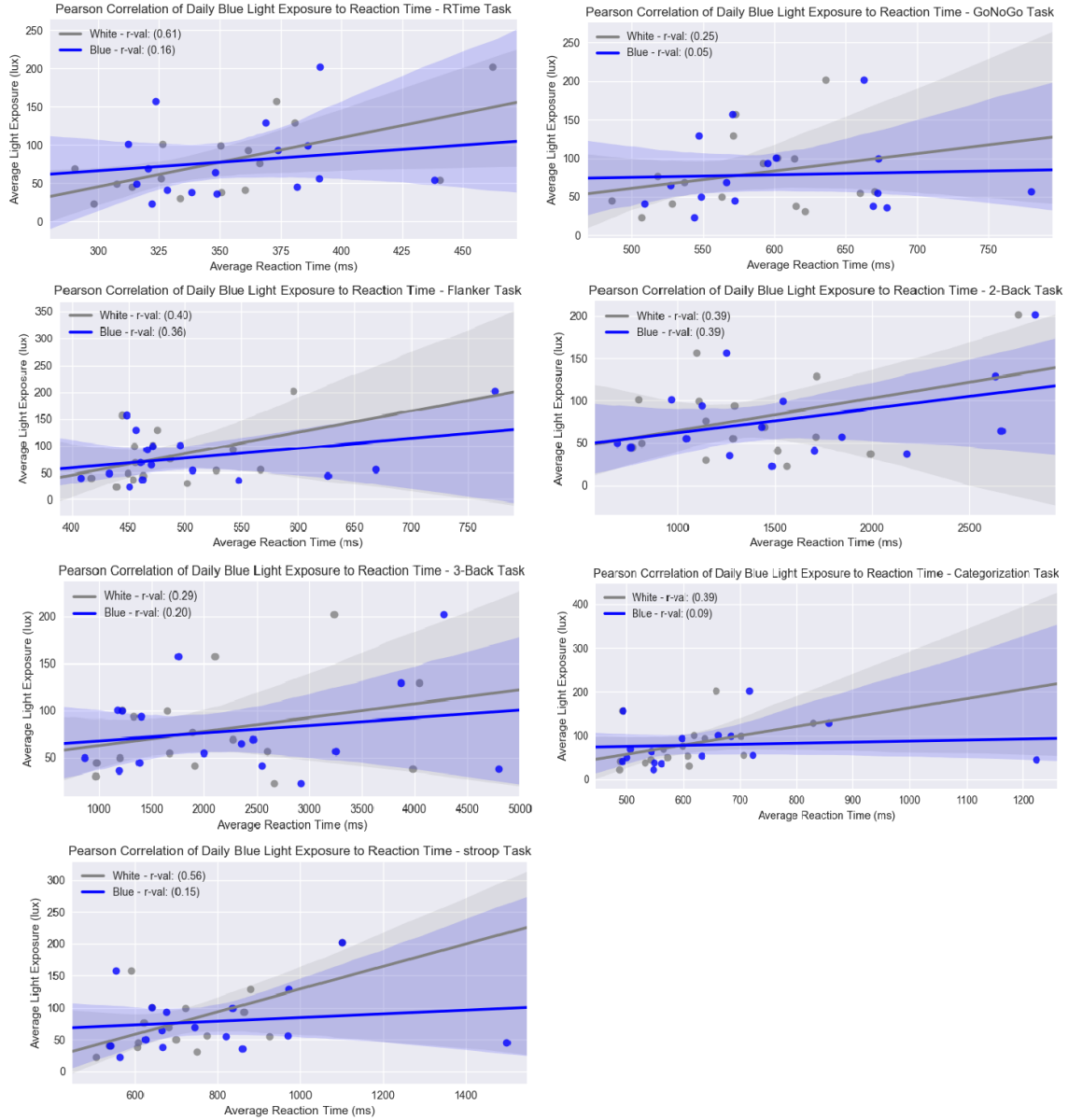


Figure 30: Pearson Correlation of Average Daily Blue Light Exposure

4.4.2. Eye Color

The eye colors of participants in this experiment were somewhat evenly distributed among participants (unintentionally). Six individuals had blue eyes, four had brown, four had hazel, one had green and one individual refrained from answering. In order to determine if eye color plays a role in how a participant is affected by pre-exposure to light, a mixed linear model was created. First, the unknown eye color

participant and the one green-eyed participant was removed from the data. Then, the models were fitted with the ordinary least squares (ols) function from the Python package statsmodels. Models with and without interaction effects were created, but the coefficients for the interaction effects were very high. Therefore, only the models without interaction effects were reported. The results from the final linear models can be seen in Table 26.

Table 26: Linear Model for Eye Color

	<i>Reaction Time</i>				<i>Go/No-Go</i>			
	Coef.	Std.Err.	z	P> z	Coef.	Std.Err.	z	P> z
<i>Intercept</i>	356.8805	7.044	50.666	0.000	616.4859	5.334	115.585	0.000
<i>C(Eyes)[T.Brown]</i>	-17.9307	9.318	-1.924	0.054	-32.5339	7.082	-4.594	0.000
<i>C(Eyes)[T.Hazel]</i>	6.0065	9.341	0.643	0.520	-34.1782	7.05	-4.848	0.000
<i>C(Color)[T.white]</i>	0.3692	7.724	0.048	0.962	-21.7741	5.851	-3.722	0.000
<i>Prob(F)</i>	= 0.109				= 7.22×10^{-10}			
	<i>Flanker</i>				<i>2-Back</i>			
	Coef.	Std.Err.	z	P> z	Coef.	Std.Err.	z	P> z
<i>Intercept</i>	540.7339	14.102	38.344	0.000	1787.323	53.364	33.493	0.000
<i>C(Eyes)[T.Brown]</i>	-54.0388	18.655	-2.897	0.004	-355.927	70.595	-5.042	0.000
<i>C(Eyes)[T.Hazel]</i>	-57.105	18.655	-3.061	0.002	-249.145	70.595	-3.529	0.000
<i>C(Color)[T.white]</i>	-24.1889	15.448	-1.566	0.118	-194.558	58.458	-3.328	0.001
<i>Prob(F)</i>	= 0.00172				= 2.03×10^{-8}			
	<i>3-Back</i>				<i>Categorization</i>			
	Coef.	Std.Err.	z	P> z	Coef.	Std.Err.	z	P> z
<i>Intercept</i>	2706.876	83.901	32.263	0.000	680.7448	7.725	88.126	0.000
<i>C(Eyes)[T.Brown]</i>	-315.639	110.991	-2.844	0.005	-16.9621	10.219	-1.66	0.097
<i>C(Eyes)[T.Hazel]</i>	-397.434	110.991	-3.581	0.000	-105.208	10.219	-10.296	0.000
<i>C(Color)[T.white]</i>	-282.019	91.909	-3.068	0.002	-50.3755	8.462	-5.953	0.000
<i>Prob(F)</i>	= 2.06×10^{-5}				= 2.52×10^{-31}			
	<i>Stroop</i>							
	Coef.	Std.Err.	z	P> z				
<i>Intercept</i>	875.7625	16.673	52.526	0.000				
<i>C(Eyes)[T.Brown]</i>	-123.24	22.056	-5.588	0.000				
<i>C(Eyes)[T.Hazel]</i>	-184.561	22.056	-8.368	0.000				
<i>C(Color)[T.white]</i>	-72.0655	18.264	-3.946	0.000				
<i>Prob(F)</i>	= 2.13×10^{-19}							

Similar to the discussion in 4.3.7, the z value in the results is the coefficient divided by the standard error. The hope is to have a small standard error that is at least 4 or 5 times less than the coefficient. The z value indicates how much smaller/larger the standard error actually is. In most cases, the standard error is low enough so that the $P > |z|$ value is also low with the exception of the RTT. The $Prob(F)$ result is the probability that the null hypothesis of the actual model is true. Again, in all cases with the exception of the RTT, this probability is low (below 0.05).

As can be seen in the table, the blue eye trait is not listed. Instead, it is hidden in the intercept of the model, but in almost all cases for the other eye colors, the coefficient is negative. This implies that other eye colors result in faster response times than blue eyes. This is in opposition to the findings from previous studies which showed that a light treatment caused the blue-eyed participants to respond faster than non-blue-eyed participants, but it is important to point out that eye color was not controlled in this experiment nor the previous one. This causes the analysis of eye color being an observational study. Therefore, the data may not produce any meaningful information.

4.5. Summary

While the statistical significance of a few of the analysis techniques presented in this section were low, the participants' performance in this experiment showed a preference for the white pre-exposure condition in most instances. The Stanford Sleepiness Scale showed less of an alertness decrement between the start of the cognitive testing and the end of the cognitive testing after pre-exposure to the white condition. The Wilcoxon analysis of the cognitive tests showed an improvement under the white condition when compared to the blue condition, but they were not statistically significant.

However, the linear models showed a clear and statistically significant improvement under the white light condition.

An important thing to note in much of the data is that the tasks that required a decision to be made expressed a more statistically significant improvement with the white condition than the blue condition. This was especially true of the Go/No-Go test where the statistical significance of improved response time was apparent in all analyses. Go/No-Go specifically measured the cognitive responses of response time and response control. However, the RTT, which solely looks at response time without requiring a participant to make a decision was not statistically significant. This may imply that the white light condition did more to assist in response control than it did to aid in response time without requiring a decision to be made. However, accuracy and other analyses involving how well a participant performed on the test did not seem to be affected by either pre-exposure condition. This is consistent with other literature and likely implies that light exposure doesn't cause a participant to perform more accurately, but instead to perform faster.

V. Conclusions and Recommendations

5.1. Chapter Overview

Throughout the Air Force many personnel are asked to work in suboptimal lighting conditions with work shifts that can cause severe circadian rhythm disruptions leading to lowered alertness and cognitive abilities. This thesis sought a solution to this problem by exploring whether 30-minutes of exposure to a blue lit room would improve the cognitive performance of a human over white light. Based on previous research, the hypothesis in this case was that the blue light would cause an improvement over white light. In order to evaluate the hypothesis, six cognitive measurements were administered to 16 participants. Response time, accuracy, eye movements, brain activity, daily light exposure and subjective sleepiness scores were recorded. This chapter summarizes the findings from that experiment and demonstrates how each measurement related to the hypotheses. Additionally, it further delves into the significance of the research and recommends future actions and research.

5.2. Conclusions of Research

This research determined if the pre-exposure to blue light induced a greater positive cognitive effect than white light. To do this, participants' sleep and light exposure was tracked for a minimum of 48 hours. Afterwards, participants were exposed to 30-minutes of both blue or white light (on separate days) prior to performing six different cognitive tasks and answering seven instances of the Stanford Sleepiness Scale (SSS). Additionally, electroencephalographic (EEG) and electrooculographic (EOG) data were recorded, but not used in this research. The data collected during the entire research period was analyzed to determine the effect of the light exposure. The averages for each

participant in each test is shown in Appendices A and B. To perform the analysis, the data was subjected to a two-sided Wilcoxon signed-rank test and linear models of the data were created. These provided a p-value which could be used to determine the statistical significance of the data. Overall, the blue pre-exposure condition failed to indicate better performance than the white pre-exposure condition, but the statistical significance of the improvement varied by the test.

In the case of the SSS, the mean value of the white condition was 0.02 points lower (more alert) than the blue condition. However, the difference in mean alertness level was negligible considering that the questionnaire is on a 7-point scale. The lack of difference between the two conditions was demonstrated by the data's low statistical significance with a p-value of 0.65. When analyzing the responses to the SSS over time, the blue condition, again, tended to result in higher SSS scores as time passed (more fatigued), but the difference was minimal and not statistically significant (*p*-values of 0.33 to 0.85 for each iteration). The analysis that provided the best results from the SSS data came from finding the difference between the first time the SSS was given and the last time the SSS was given. The white condition resulted in a mean of a 0.56 increase in points (fatigue increase) and the blue condition resulted in a 1.13 increase in points. The p-value for this comparison was 0.14, which is still not considered statistically significant. However, the lack of statistical significance in the SSS data may have been a result of having insufficient data points. At least 20 points are recommended and this analysis used 32, but 100 or more may have resulted in more influential data. Further testing with more participants would be required to determine the significance.

The cognitive tests measured response time, accuracy, response time for correct answers, response time for incorrect answers and cognitive throughput. The response time and cognitive throughput measurements showed an improved cognitive response for pre-exposure to the white condition for all tasks. Response time for correct answers showed improved cognitive response under the white condition on all tasks except the categorization task. However, when comparing average participant responses, only the Go/No-Go (GNG) task (measures the response time and response control dependent variables) induced enough of an effect to be statistically significant. This may have been due to a lack of data points (32 data points per test when using averages). Similar to previous research, accuracy was unchanged regardless of the pre-exposure light condition.

When comparing individual stimulus response times, more participants had improved response times under the white condition than the blue condition. Additionally, the mixed effects linear model that was fit to the data showed a clear improvement in the white condition over the blue condition in all models with the exception of the Reaction Time Test (RTT) and the Flanker Test. In those two tasks, the model fit a preference for improvement under the white condition, but the standard error was too high to ensure the model could accurately predict the effects on the population. There was also an apparent interaction effect between the light color and selecting a correct answer. While selecting a correct answer in both lighting conditions corresponded to a faster response time, in the white light condition, the difference in response time between selecting a correct or incorrect answer was minimized.

In order to look at the potential of diminishing effects in long term blue light exposure, the average amount of blue light a participant was exposed to during the day was compared to their response time under both the blue and white conditions. Additionally, the difference in their response times under the blue and white conditions was compared with their average blue light exposure. While it is important to note that daily blue light exposure was not controlled for in this experiment and therefore the analysis is considered observational, in every case an increase in daily blue light exposure was correlated with a slower response time. However, the only times this correlation was statistically significant was under the white pre-exposure condition for RTT (p-value = 0.01) and the Stroop (p-value = 0.02) task. Additionally, the white pre-exposure condition was more negatively affected by the increase in light than the blue condition in all tasks except the Flanker task and the 2-back task. However, the only statistically significant task which showed the white pre-exposure task being more affected was the RTT (p-value = 0.01). It's difficult to determine what this might mean, and more work must be done in this area to determine the significance of the finding.

Eye color analysis used a linear fixed effects model to determine the effect of response time after the light pre-exposure. Eye color played a significant role in the model. In fact, in most cases, eye color seemed to relate more to response time than the pre-exposure condition did. Additionally, the coefficients for eye color were relatively high and the standard error was relatively low. However, in almost all cases the coefficients of the non-blue eye colors were negative (exception was RTT: Hazel) while the blue eye condition's coefficient was represented by the intercept of the model. The implication of this is that blue eyes generally result in a slower response time than the

other eye colors. This opposes previous research. However, it is possible that all of the blue-eyed participants were inherently slower and not representative of the population. Further studies with more participants and evenly spread eye colors would be useful to determine if this is a significant finding.

5.3. Significance of Research

The research presented in this thesis showed that blue light may not always impart improved cognitive effects over other colors of light. White light is multi-spectrum light which means it contains multiple colors/wavelengths of light. The white light used in this experiment had a correlated color temperature of D6500 which is a commonly used standard light color. It is a light color used in some workplaces, but is mostly used as a standard for color matching. Its slight bluish hue mimics natural daylight. It is likely that this light color contained enough blue light to stimulate the ipRGCs. More research would be required to determine why the blue light condition did not perform as well. However, it is possible that the excess blue light resulted in an overstimulation and caused the blue light within the white light to achieve the desired effect instead. Regardless, this research overwhelmingly showed that narrowband blue light failed to improve cognitive performance when compared to bright, broad spectrum white light. In light of that information, there is no advantage to using blue light instead of white light in breakrooms and other common areas.

5.4. Recommendations for Future Research

There are various ways this research could be altered to either gain more information about the topic or further refine already analyzed data. A few of those recommendations are listed in this section.

5.4.1. Other Light Colors

Due to time constraints and participant availability, only two different colors of light could be analyzed. As mentioned in section 3.10.3.4 and seen in Figure 16, white light is composed of varying intensities of many different wavelengths of light. Added together, the combination of light colors makes the light appear white to the human eye, but there is no single white light wavelength. Additionally, some variation of blue light is needed to create the white light color. This is especially true when using a “cooler” correlated color temperature such as D65 as was used in this experiment. Due to this fact, it was difficult to determine if it was the blue light within the white multi-spectrum light that was causing a non-visual effect and perhaps the blue light alone may have caused an improvement over a different wavelength such as amber or red. Due to that possibility, it would be useful to complete the same experiment using another wavelength of light. As an added benefit, the analysis of red light could prove useful to military operations since some operators work under red ambient lighting conditions to utilize the night vision preserving qualities of red light.

5.4.2. Diminishing Effect with Increased Exposure to Blue Light

Some of the analysis findings in this research suggested that increased exposure to blue light may result in light having a reduced effect on response time. The potential implication of this is that as the body adjusts to more light, the light becomes less effective. This is similar to a person becoming a caffeine tolerant or becoming tolerant to other alerting drugs. However, this portion of the research was only observational since the amount of blue light a person received outside of the experiment was not controlled.

Further research would be required to determine if this analysis was statistically significant.

5.4.3. Effect of Choice

Much of the analysis in this research seemed to point to the fact that a simple reaction time (RT) test (one stimulus type and one response) was less affected by the pre-exposure than a choice RT test (multiple stimulus types and multiple responses). The difference between the two types of test was detailed by FC Donders in 1868 where he noted that it took longer to complete a choice RT test than a simple one. He proposed the idea of the subtraction method in which the time taken in the simple RT could be subtracted from the choice RT to determine the length of discrimination and choice stages of mental processing [11]. However, this technique has been highly criticized and new methods have been found that are theorized to do a better job at determining how to calculate the time needed for different types of mental processes. To effectively measure how blue light effects those stages, the experiment and tests must be selected to specifically test this phenomenon. A method that is considered better for studying this topic is Saul Sternberg's Additive Method where he suggests using the same test multiple times, but degrading different parts of the test at different times. The degraded parts will cause the participant to take longer to respond based on the mental process that is required to overcome the degradation. The degraded response can be compared to the non-degraded response to determine the length of time taken in each stage [72]. Research in this area could help determine where, exactly, in the decision process blue light is able to have the greatest effect.

5.4.4. Physiological Recording Analysis

While physiological data was recorded, physiological measures were not analyzed in this work. However, analysis of the physiological measures can result in a further understanding of the alertness and fatigue felt by the participant. In much of lighting literature, one way to analyze EEG data is to split the data into 2-second epochs which are then run through the fast Fourier transform algorithm. The power density is broken up into 0.5 Hz bins for frequencies between 1 and 20 Hz. From that point, it is possible to review the average percentage of the power density for each frequency. An example of how this can be visually expressed is shown in Figure 31. Since alertness is associated with lower power in the theta-alpha frequencies and increased power in the high-alpha frequencies, each frequency can be compared to determine if that phenomenon occurred. After visually inspecting the data, the average power density of each participant could be used to perform a Wilcoxon test to determine the statistical significance of the results.

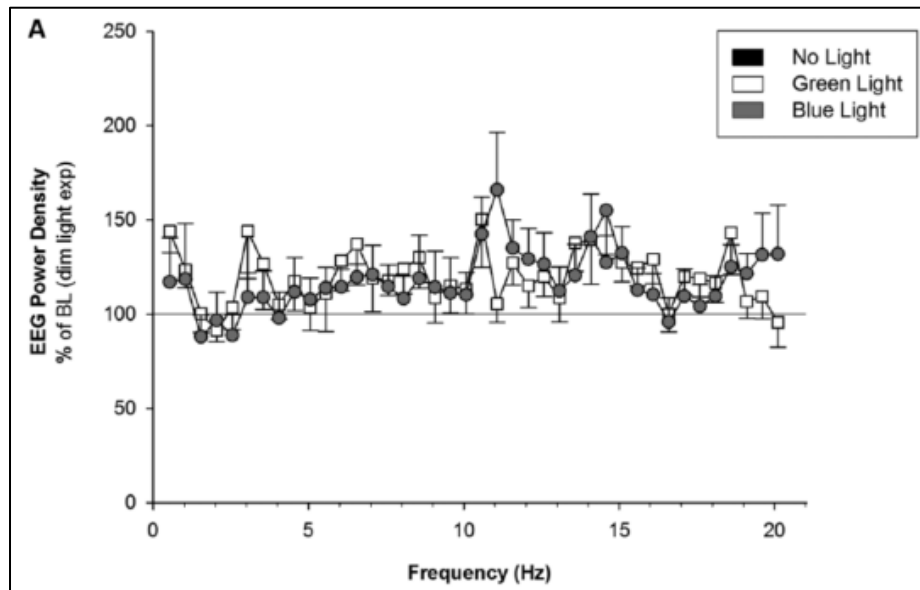


Figure 31: Example EEG Profile [35]

Another common analysis technique analyzes Event Related Potentials (ERPs). The utility of this method and directions on how to use it are further explained in section 2.3.2.1. However, an ERP is essentially the average waveform of an EEG epoch that is time-locked to a stimulus [33]. The average of the waveforms is found and results in a wave that represents brain activity for the type of stimulus being measured. To evaluate alertness, peak P3 (or P300) is analyzed. Increased fatigue is most generally associated with a lower amplitude and longer latency of that peak [44].

EOG measures the power detected by the electrodes in μV over time. As a person starts to blink or begins to move their eyes, the power begins to increase until the height of the movement. Then, as the movement stops, the power decreases until the power returns to normal. In the EOG output this appears as a wave or a spike as seen in Figure 32. Since an increase in Slow eye movements (SEMs) and blinks have been shown to indicate decreased alertness [10], measuring the number of SEMs and blinks during multiple 1-minute epochs should indicate the rate of deteriorating alertness. Slow eye movements (SEMs) and blinks can be measured by identifying the start of an increase in power until the moment when the power returns to normal. SEMs can be defined as slow ($< 0.25 \text{ Hz}$), rolling eye movements ($> 100 \sim \mu\text{V}$) lasting for more than 1 sec [35], [73] and can be identified in the vertical EOG recording. Blinks can also be identified in the vertical recording and are indicated by a spike in amplitude (normally $100\text{-}400 \mu\text{V}$) lasting from $100\text{-}400 \text{ ms}$ [74].

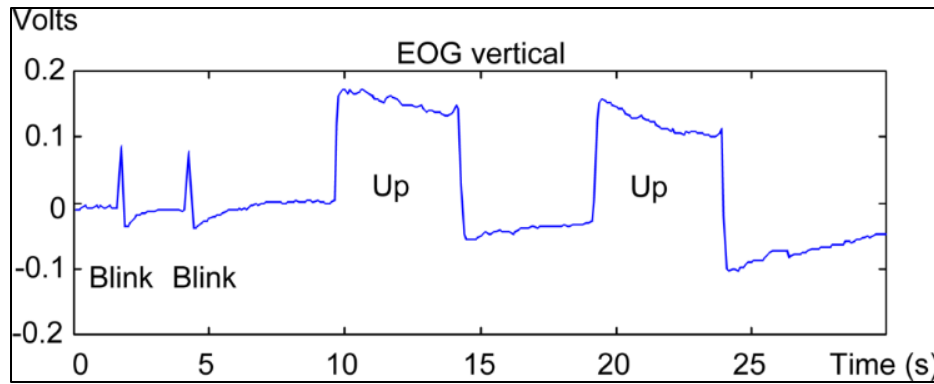


Figure 32: Blinking and Upward Saccadic Movement in Vertical EOG Sensors [75]

5.5. Summary

This research showed that pre-exposure to high intensity blue light did not cause a significant cognitive performance improvement over white light when a participant worked in a low-lit room. In fact, white light was shown to have an improvement over blue light in regards to response time when analyzed via a mixed linear model. However, when considering response time without a decision being made like in the RTT, there was no improvement. Similar to previous studies, accuracy did not improve with either light condition, but since the accuracy was very high in all tasks any improvements may have been not possible to determine. More difficult tasks may be required to determine if accuracy is affected. Additionally, this research suggests that the previous study that indicated that blue eyes react better to light pre-exposure than other colors of eyes is false. Further studies are required to determine how eye color affects a light treatment.

Appendix A: Accuracy Results

Each participant received an accuracy score (in percent) for each cognitive task.

Accuracy was chosen rather than error count or correct answers since each test had a different number of questions. Go/No-Go was time based (4 minutes) rather than question number based, but each participant did exactly 91 iterations of the test. The Eriksen Flanker task had 96 total questions split evenly among the possible conditions (congruent/incongruent and left/right). 2-back and 3-back had 50 questions each, with 60% of the answers being false (not seen n iterations ago). Categorization had 120 questions, split evenly between the two conditions. The Stroop task had 96 total questions split evenly among the possible conditions (congruent/incongruent and red/green/blue).

The following table provides the exact accuracy amount for each participant per test.

Table 27: Accuracy Results for Cognitive Tasks

<i>Task</i>	<i>Go/No-Go</i>	<i>Go/No-Go</i>	<i>Flanker</i>	<i>Flanker</i>	<i>2-Back</i>	<i>2-Back</i>	<i>3-Back</i>	<i>3-Back</i>	<i>Categ</i>	<i>Categ</i>	<i>Stroop</i>	<i>Stroop</i>
<i>Color</i>	<i>White</i>	<i>Blue</i>	<i>White</i>	<i>Blue</i>	<i>White</i>	<i>Blue</i>	<i>White</i>	<i>Blue</i>	<i>White</i>	<i>Blue</i>	<i>White</i>	<i>Blue</i>
1336	95.60	96.70	98.96	97.92	100.0	100.0	100.0	100.0	97.50	95.83	98.96	98.96
2339	100.0	97.80	97.92	100.00	97.96	100.0	93.88	100.0	98.33	96.67	98.96	100.00
2436	98.90	98.90	100.00	100.00	100.0	100.0	100.0	95.92	98.33	97.50	98.96	97.92
2767	97.80	97.80	98.96	100.00	95.92	97.96	97.96	83.67	95.83	96.67	95.83	98.96
2861	100.0	100.00	100.00	98.96	100.0	100.0	100.0	97.96	100.0	96.67	100.0	97.92
4836	94.51	76.92	89.58	83.33	97.96	91.84	91.84	79.59	95.00	52.50	89.58	88.54
5435	92.31	95.60	95.83	98.96	14.29	91.84	81.63	95.92	95.00	98.33	100.0	95.83
6039	97.80	100.0	98.96	96.88	100.0	71.43	91.84	93.88	96.67	96.67	97.92	98.96
6208	98.90	100.0	100.0	98.96	93.88	97.96	97.96	91.84	100.0	96.67	100.0	98.96
6336	98.90	97.80	98.96	100.00	100.0	100.0	100.0	100.0	96.67	100.0	100.0	98.96
6600	98.90	96.70	98.96	100.00	100.0	100.0	93.88	93.88	95.83	97.50	97.92	95.83
7211	95.60	91.21	96.88	98.96	97.96	100.0	93.88	87.76	95.83	99.17	92.71	94.79
7523	97.80	97.80	98.96	94.79	97.96	87.76	89.80	81.63	98.33	98.33	96.88	97.92
8828	95.60	100.00	97.92	100.00	93.88	97.96	85.71	91.84	99.17	99.17	97.92	100.0
9110	100.00	97.80	97.92	100.00	87.76	85.71	77.55	79.59	99.17	100.0	98.96	100.0
9672	95.60	97.80	97.92	95.83	91.84	97.96	97.96	97.96	95.00	97.50	93.75	95.83
Avg	97.39	96.43	97.98	97.79	91.84	95.03	93.37	91.96	97.29	94.95	97.40	97.46
STD	2.19	5.46	2.43	4.05	20.32	7.60	6.63	7.09	1.73	11.03	2.92	2.80

Appendix B: Average Response Time Results

The following table outlines the average response times (ms) for each task per participant. This is the data that was used for the paired Wilcoxon test in chapter 4.

Table 28: Average Response times (ms)

<i>Task</i>	<i>RT</i>	<i>RT</i>	<i>Go/</i>	<i>Go/</i>	<i>Flk</i>	<i>Flk</i>	<i>2-</i>	<i>2-</i>	<i>3-</i>	<i>3-</i>	<i>Catg</i>	<i>Catg</i>	<i>Strp</i>	<i>Strp</i>
<i>Color</i>	<i>W</i>	<i>B</i>	<i>NG</i>	<i>NG</i>	<i>W</i>	<i>B</i>	<i>Back</i>	<i>Back</i>	<i>Back</i>	<i>Back</i>	<i>W</i>	<i>B</i>	<i>W</i>	<i>B</i>
1336	360	328	528	509	417	408	1512	1701	1910	2547	490	492	537	540
2339	350	386	614	673	456	471	1111	1538	1653	1219	701	683	721	835
2436	298	322	507	544	439	451	1558	1484	2665	2919	488	548	505	562
2767	373	324	573	571	444	448	1096	1251	2103	1755	492	494	591	553
2861	381	369	571	547	475	457	1716	2633	4038	3871	829	856	876	972
4836	314	382	486	572	463	626	766	758	978	1385	543	1223	607	1498
5435	362	374	592	595	542	467	1292	1124	1328	1397	638	597	862	676
6039	366	348	518	527	487	470	1146	2663	1890	2350	598	544	621	664
6208	327	312	602	601	471	495	798	969	1223	1175	618	661	639	639
6336	351	338	615	669	454	462	1991	2177	3985	4800	533	549	605	666
6600	308	316	563	549	449	433	814	687	1195	863	572	500	699	625
7211	441	438	660	672	527	507	1283	1046	1669	1997	607	632	924	821
7523	290	320	537	567	456	461	1446	1430	2275	2463	565	506	682	742
8828	326	391	670	780	567	669	1710	1845	2600	3248	706	723	773	970
9110	334	349	621	679	502	548	1148	1266	966	1189	609	562	748	859
9672	462	391	636	663	596	773	2750	2834	3238	4275	658	716	1099	1100
Avg	353	356	581	607	484	509	1384	1588	2107	2341	603	643	718	795
STD														

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14. ABSTRACT This thesis research looks at the effects of short duration, high intensity, short wavelength light with the goal of determining if converting typically white colored lights in breakrooms and bathrooms to blue will cause workers who normally work in a low light environment to be more alert and productive. Sixteen participants were outfitted with Electroencephalography (and Electrooculography (EOG) equipment before being exposed to 200 lux of either 460 nm blue light or D6500 white light for 30 minutes. Afterwards, the light levels were changed to 3.5 lux of D6500 light and the participants were asked to perform six cognitive tests that were selected to measure response time, response control, selective attention, working memory and semantic memory. Results showed that the white light condition improved response time over blue light in tasks that required a choice to be made but had no effect on accuracy. Similarly, subjective alertness as measured from the Stanford Sleepiness Scale showed a lower decrement in alertness over time in the white condition over the blue condition, but initial alertness was less affected.					
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