MEASURING EYE FATIGUE OF RADIOLOGIST AT READING ROOM AND DAYLIGHT ILLUMINATION CONDITIONS

by

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ABSTRACT

MEASURING EYE FATIGUE OF RADIOLOGIST AT READING ROOM AND DAYLIGHT ILLUMINATION CONDITIONS

With the revolutionary development in technology, diagnostics methods that are used in radiology have started to change with visual display terminals; however, traditionally the ambient light should be as low as feasible in order to maintain image contrast which may have a negative effect on the amount of eye fatigue of radiologists. The main objective of this study is to investigate the relation between the eye fatigue and ambient light as well as to show the amount of eye fatigue at reading room (0, 50 lux) and daylight (500 lux) conditions using three different eye fatigue measurements methods (CFF, Eye Blink rate (EB), Subjective Test (ST)). In order to stimulate eye fatigue, 400 X-ray chest images with pre-marked nodules were given to the five non-radiologist subjects for evaluation under three different ambient lighting settings. Each image was present on the screen for 10 seconds; therefore one session took 66 minutes for each subject to complete and was repeated for each ambient lighting settings. Measurements were taken before and after each session. Repeated measures ANOVA for eye blink results showed that there was a trend to be significant ($p=0.065$) and pairwise comparison showed that the difference in respect of eye fatigue came from mainly the difference between 0 - 50 lux ($p=0.061$) as well as 0 - 500 lux ($p=0.045$). According to the Friedman statistics for subjective test, subjects felt significantly different fatigue under different ambient lighting settings ($p=0.008$). There was a trend to be significant correlation between ST and CFF and between ST and EB at 0 lux ($p = 0.065$ and 0.068 respectively). In conclusion, eye fatigue was found to be diminishing with increasing ambient light between 0 and 50 lux and between 0 and 500 lux; however, there was no statistically significant difference between 50 and 500 lux.

Keywords: Radiology, Eye Fatigue, Critical Flicker Frequency, Eye Blink, Ambient Lighting

ÖZET

RADYOLOJİ TANI ODASI VE GÜN IŞIĞI AYDINLATMA KOŞULLARINDA RADYOLOGLARIN GÖZ YORGUNLUĞUNUN ÖLÇÜLMESİ

Gelişen teknoloji ile birlikte, radyolojide kullanılan tanı koyma yöntemleri dijital ekranlarla değiştirilmeye başladı ancak geleneksel olarak görüntüdeki kontrastı korumak için ortam ışığının mümkün olduğunca düşük olması gerekiyor ki düşük ışıklarda çalışmak radyologların göz yorgunluğu miktarını negatif yönde etkiliyor. Bu çalışmanın ana amacı göz yorgunluğu ve ortam ışığı arasındaki ilişkiyi incelemek ve aynı zamanda radyoloji tanı koyma odasında ki ortam ışık miktarıyla (0 ve 50 lux) günışığı koşullarında (500 lux) göz yorgunluğu miktarını üç faklı yöntem (Kritik Titreşim Frekansı, Göz Kırpma Miktarı ve Öznel Test) kullanarak ölçmek. Göz yorgunluğu oluşturmak için her bir ışık miktarı altında, üzerinde ki modüller daha önceden işaretlenmiş olan 400 adet x-ray göğüs görüntüsü radyolog olmayan beş deneğe puanlamaları için verildi. Her bir görüntü ekranda 10 saniye boyunca gösterildi ve her bir seans toplamda 66 dakika sürdü. Ölçümler her bir seansın öncesinde ve sonrasında alındı. Göz kırpma için tekrarlayan ölçümlerde varyans analizi sonuçları önemli bir farklılık olabilme ihtimali olduğunu gösteriyor ($p=0.065$) ve bu fark çoğunlukla 0-50 lux ($p = 0.061$) ve 0-500 ($p = 0.045$) lux arasında ki farktan kaynaklanıyor. Öznel test için Friedman istatistiğine göre farklı ortam ışıklarında ki göz yorgunlukları arasında önemli bir fark var ($p=0.008$). Korelasyon sonuçlarına göre, 0 lux' te öznel test ile kiritik titreşim frekansı arasında ($p = 0.065$) ve öznel test ile göz kırpma miktarı arasında ($p = 0.068$) önemli bir sonuç olabilme ihtimali var. Sonuç olarak, bu çalışmaya göre göz yorgunluğu 0 ile 50 lüks arasında ve 0 ile 500 lüks arasında artan ortam ışığıyla azalıyor; ancak 50 ve 500 lüks arasında istatiksel olarak anlamlı herhangi bir fark bulunmuyor.

Anahtar Sözcükler: Radyoloji, Göz Yogunluğu, Kritik Titreşim Frekansı, Göz Kırpma, Ortam Aydınlatması

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LIST OF SYMBOLS

cd/m^2	Candela per square-meter
m^2	Square-meter
mm	Millimeter
Hz	Herz
min	Minute
N	Number of Subjects
F	Critical Value of ANOVA
t	Critical Value of Paired t-test
Z	Critical Value of Friedman Statistics
p	Significance Value

LIST OF ABBREVIATIONS

PACS	Picture Archiving and Communication System
DICOM	Digital Imaging and Communications in Medicine
ACR	American College of Radiology
NEMA	National Electrical Manufacturers Association
HIS	Hospital Information System
RIS	Radiology Information System
AAPM	American Association of Physicist in Medicine
RANZCR	The Royal Australian and New Zealand College of Radiologists
CEC	Commission of the European Communities
CFF	Critical Flicker Frequency
JSRT	Japanese Society of Radiological Technology
MRI	Magnetic Resonance Imaging
CT	Computed Tomography
JRS	Japanese Radiological Society
WHO	World Health Organization
NIH	National Institute of Health
VGAS	Visual Grading Analysis Statistics
LUTs	Look-up Tables
LED	Light Emitting Diode
IR	Infrared
LCD	Liquid Crystal Display
RGB	Red Green Blue
ANOVA	Analysis of Variance
Std.	Standard
Sig.	Significance
Coeff.	Coefficient
df	Degrees of Freedom

1. INTRODUCTION

1.1 Background and Motivation

With the revolutionary development in technology, traditional reading techniques in radiology are replaced by digital techniques. Traditionally, the images taken by Rontgen are printed on films which are then presented to radiologist for diagnosis purposes. By using a light box, radiologists are able to read the films in order to find the anomalies and it is still considered as a gold standard by radiologists because of the image quality and contrast that films are able to provide.

In 1982, Duerincxk et al. [1] introduced the filmless Picture Archiving and Communication System (PACS). Basically, PACS is a network system that consists of a server which is located in the hospital and the client computers in order to send and receive the images. Moreover, the Hospital Information System (HIS) and Radiology Information System (RIS) applications can also connect to this network to access the stored patient diagnostics data as well as previous diagnostics of patients to deliver more convenient treatment right away. In order to communicate and process images that are acquired by different imaging device vendors, in 1982, a standard protocol was introduced by American College of Radiology (ACR) and National Electrical Manufacturers Association (NEMA) which is called Digital Imaging and Communications in Medicine (DICOM) [2], and in 1985 first generation of this protocol was published. As DICOM standards are implemented by different vendors to their imaging devices, PACS has become more and more useful. Although the installation and maintenance costs of PACS is too high, there are various advantages of the system that outweigh the cost. The main advantages of the system are that the images are created, stored and secured digitally, it cannot be lost or misfiled, as well as once the images are acquired, radiologist can access the images using any computer on the network simultaneously which save considerable time for both patient and hospital.

In order to use the advantages of PACS, light box should be replaced by medical-grade display. Using medical-grade displays instead of light box; however, brings some disadvantages like decreased level of contrast, luminance, and spatial resolution. Whereas, higher contrast provides higher differentiation between two structure, higher luminance makes the darker regions more visible, higher spatial resolution means that the display terminal can show more detailed images. Since the spatial resolution of traditional film is 15 pair per millimeter [3] and the luminance of light box could be as high as 3000 cd/m^2 [4] which are still not reachable even by medical-grade display, to prevent misdiagnosis and maintain the perceived image contrast, the environmental conditions of radiologist reading room and the minimum technical specifications required by medical-grade displays are clearly stated in the several standards. One of the conditions to preserve image quality is the ambient light of reading room. While there is no universal standard for ambient lighting levels of reading rooms, conventionally, the ambient lighting of reading room should be as much as low in order to prevent any glare on the screen which could decrease the contrast in dark regions.

Although the light levels that are suggested by European Standards should be around 500 lux for office environments where employees are working with display terminals [5], radiology reading room standards that were published by various committees suggested that the ambient light should not exceed 50 lux in general in order to restrain misdiagnosis. There is no universal standard about the proper level of ambient light of reading room in radiology department; however, according to American Association of Physicist in Medicine (AAPM) Report no:3 [6] ambient lighting section clearly suggested that the amount of ambient light should be between 2 and 10 lux for x-ray diagnostic purposes which is actually no more than the display itself provides alone and should be between 40 and 60 lux for Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) diagnostic purposes, whereas the standard that were published by The Royal Australian and New Zealand College of Radiologists (RANZCR) [7] suggested that the ambient light should be between 20-40 lux in reading rooms for all diagnostic purposes. More than that, American College of Radiology (ACR) suggested that the ambient light should not exceed 50 lux in order to diagnose mammogram images. At the time that the light boxes were widely used more than digital displays, World Health Organization (WHO) [8] and Commission of the European Communities (CEC) [9] recommended that the ambient light should not be more than 100 lux at 30 cm from the display and 50 lux at 100cm from the display respectively. On the other hand, working in an environment that is not well enlighten can cause depression due to the decreased levels of neurons that produce norepinephrine, dopamine and serotonin which are common neurotransmitters that are responsible for emotion, pleasure and cognition [10] and also there are studies that show the less exposure to light can affect the circadian system which could be described as basically the 24-hour system that keep the individual's body balance [11]. Furthermore, the greater the difference in illuminance between the display terminal and the surrounding area, the greater the amount of eye fatigue experienced by the radiologist, because of the eye muscles will constantly try to adapt between the display terminal and the surrounding area, which will cause eventually increased eye fatigue and decrease the performance of radiologist [12].

There are several measurement techniques for eye fatigue level such as accommodation power, pupil diameter, Critical Flicker Frequency (CFF), eye blink rate and subjective test [13]. One of the most powerful technique among them is CFF which is the threshold frequency of a flickering stimulus where it starts to appear as a continuous stimulus or vice versa [14]. There are some factors that could have an effect on the threshold frequency such as age, sex and environmental conditions; moreover, Maeda et al. [14] shows that after working with visual display terminals for long hours, CFF could be significantly decreased as an indicator of eye fatigue. Another way to measure eye fatigue is to count eye blinks. Since eye muscles are primarily responsible for focusing, increasing eye fatigue will cause a reduction in the number of blinks per given time frame [15]. A subjective test could also be used in order to measure eye fatigue. Indications such as headache, itchy eyes, heavy eyes, colour changes, pain around the eyes which are some of the most important symptoms of eye fatigue, can be determined by the evaluation of subjects using a Likert scale.

1.2 Literature Review

There are two different paper published in literature. Maeda et al. [14] suggested that there is a relation between eye fatigue level and critical flicker frequency. 7 radiologists participated in this experiment. They measured CFF before and after the 4-h long experiment. They also used a subjective test to show the relation between sleep durations and CFF. Results showed that after-reading subjective fatigue was significantly greater and CFF was significantly lower.

Goo et al. [16] suggested to combine the ambient light level and monitor luminance. 6 Radiologist were involved in the experiment. They used 254 chest images under three different ambient lighting level. (0, 50, 460 Lux) and three different monitor luminance levels (25, 50, 100 foot-lambert) combined. They recorded false positive and false negative and also, they measured the eye fatigue only subjectively. They reported that the subjective test score showed statistically difference due to both the ambient light and the luminance levels.

No study measured eye fatigue objectively and subjectively for chest radiography at 0, 50 and 500 lux ambient light conditions.

1.3 Objectives

Our aim is to measure objectively and subjectively eye fatigue of radiologist at reading room (0 and 50 lux) and daylight conditions (500 lux) in order to optimize reading performance (eye fatigue, perceived nodule image quality), support new studies that potentially can enable daylight reading through the use of pseudo-color using three different methods (CFF, Eye Blink Rate, Questionnaire) combined, therefore study their correlation.

1.4 Outline of Thesis

Chapter 1 gives an idea about the basic systems that are used in radiology as well as mention about the ambient light levels. State of the art and the aim of this thesis are also given in this chapter. Chapter 2 describes the experimental conditions, design and procedure and also the details about the measurement techniques that are used in this thesis. The result of the experiment is given in Chapter 3. Discussion and conclusion is in the last chapter.

2. MATERIALS AND METHODS

This study was designed to measure eye fatigue at three different ambient lights. In order to provoke eye fatigue, pre-marked x-ray images for chest and their pseudo-colored versions were shown to the observer as an assessment task to evaluate. Before and after the procedure eye fatigue measurements were taken.

2.1 Participants

Since this study was aimed to measure only the eye-fatigue, five volunteer subjects were involved instead of real radiologists. There were three women and two men with the average age of 25.4 (range 25-26). All of them were wearing contact lenses to correct myopia during the experiment whereas the average corrective dioptry was 2.80 (range 1.00-4.00) and none of them reported that they use any medication that may have effect on the vision. All of them went to an ophthalmologist within the past one year. They reported that their average sleep duration is 6.8 hours in general (range 6-8 hours). All except one work in an office environment that is illuminated with natural light. Subjects work with a computer in average of 6 hours on a daily basis (range 2-10 hours) and they complained mostly about the headache that they experience after long computer related work.

2.2 Experimental Design and Procedure

2.2.1 Room Conditions

Measurements were done in a room which had an area of approximately 12 m^2 and height of 2.5 m an it was painted to yellow matte so the reflection of light on the walls was minimum. X-ray images were displayed on an Acer Aspire 5750G laptop which has 15.6-inch display with LED backlight. The maximum resolution that the display can provide was 1366 x 768 with 200 nit brightness and 16:9 aspect ratio. The contrast of the screen was calibrated using Windows' own calibrating tools before each experiment that was done at different ambient light.

2.2.2 Ambient Lighting

The measurements were taken at three different ambient light settings 0, 50 and 500 lux. AAPM report no:3 [6] mentioned that the ambient light for x-ray diagnostic purposes should not exceed 10 lux, therefore 0 lux is selected which indicates the absence of any light source other than monitor provide by itself. As stated in the same report, the ambient light should not exceed 60 lux for Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) diagnostic purposes, whereas according to other several standards, ambient light should be set around 40 lux, so 50 lux is chosen as an average of these standards. 500 lux is preferred because according to European Standards, the ambient light should be around 500 lux for office environments where employees are working with display terminals [5]. To provide 0 lux, the room was blacked out and all the light bulbs were turned off. In order to able to adjust the ambient light to 50 and 500 lux, three light bulbs with a potentiometer were used. Using a diffuser, the potential direct glare of the light bulbs on the monitor were eliminated. As stated in of the publication of World Health Organization (WHO) [8], ambient light measurements were taken 30 cm away from the center of the display using a digital lux-meter (Figure 2.1)

2.2.3 Image Acquisition

In order to support researchers and new studies, Japanese Society of Radiological Technology (JSRT) released an online database of chest x-ray images with or without nodule in cooperation with Japanese Radiological Society (JRS) [17]. The database contains 154 nodule and 93 non-nodule images which were digitized by using Konica LD 4500 and LD 5500. The matrix resolution of the images is 2048 x 2048 with the pixel

Figure 2.1 Digital lux-meter Benetech GM1010.

size of 0.175 mm whereas the wide density range is 12 bit with 4096 gray scale. The database could be downloaded as RAW image format as well as it contains additional information like age, gender, coordinates of nodule and the degree of visual detection of nodules.

Using a dicom image viewer software such as FIJI which is one of the distribution of ImageJ, raw format images can be viewed, edited or converted to other formats. ImageJ is Java based, open source image viewer software (Figure 2.2) which is provided by National Institutes of Health (NIH). In order to import raw images properly that is downloaded by JRST database, the settings are provided in the database's manual and it is as shown in figure 2.3.

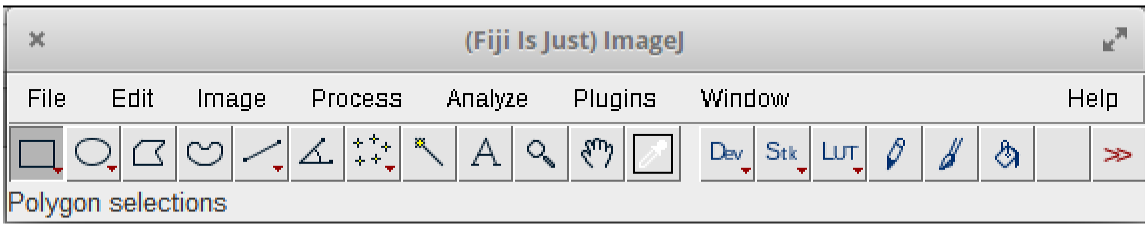


Figure 2.2 ImageJ user interface.

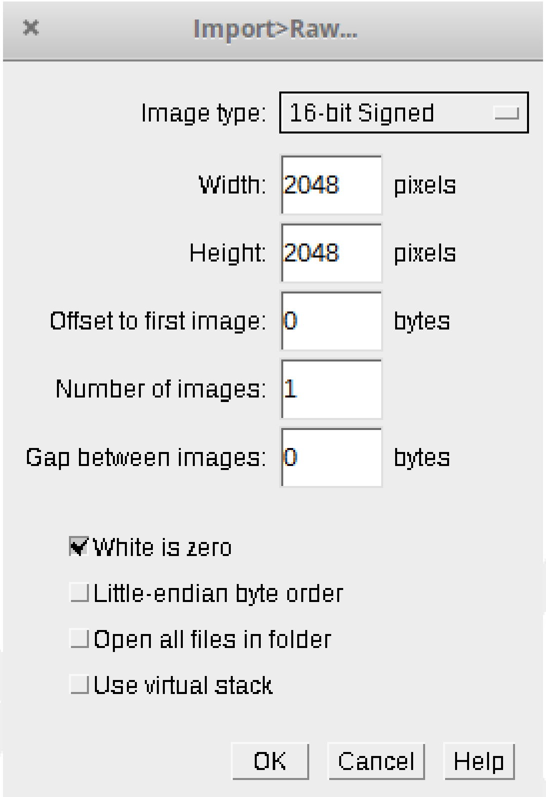


Figure 2.3 Import settings for JRST database.

Out of 154 x-ray chest images with nodule, 100 images were chosen according to their visibility degree. Then, using FIJI software, those images were converted to four different pseudo-colored versions and placed side by side with their grey-scaled versions as shown in figure 2.4. In order to create colorized version of the images, one can use predefined Look-up Tables (LUTs) or merge feature of FIJI. Luts are used in image processing to convert grey-scaled or already colored images into other color space. Since the subjects don't have radiological knowledge, an arrow was placed on the images according the coordinates that is provided by JRST. In total 400 images were evaluated by subjects using Visual Grading Analysis (VGAS) relative criteria which is shown in table 2.1, so that subjects were able to focus on the display and stimulate the eye fatigue.

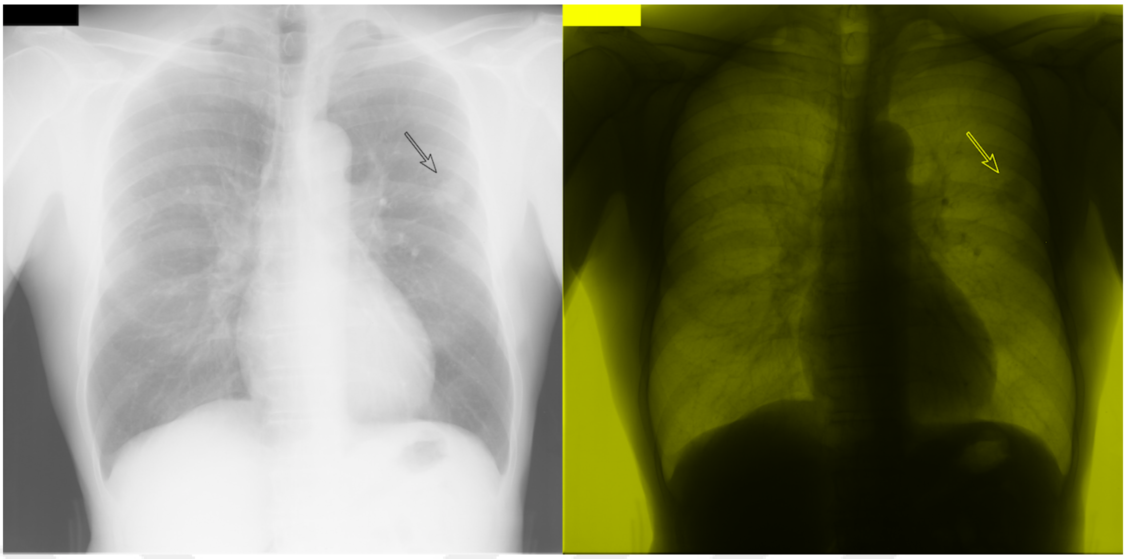


Figure 2.4 An example of visual task.

Table 2.1
VGAS - Relative image criteria.

1	Gray-scaled image clearly superior to pseudo-colored image
2	Gray-scaled image somewhat superior to pseudo-colored image
3	Both images are equal
4	Pseudo-colored image is somewhat superior to grey-scaled image
5	Pseudo-colored image clearly superior to grey-scaled image

2.2.4 Experimental Procedure

Before starting each session, the position of the laptop was checked in order to make sure that it is at the same position at every session. In order to set ambient light to the desired levels, before the experiment, measurements were done with a digital lux-meter 30 cm away from the center of the display which was followed by contrast calibration. Although the position of the laptop was fixed among the different session, subjects were allowed the adjust the viewing angle of the screen according to their point of view and were also able to evaluate images at any distance from the screen that they desired.

Prior to each session, subjects were given 10 min. accommodation time to adapt their eyes to the ambient light levels. During this period, CFF measurements were done and subjective test were given to the subjects and also a preview of another set of images were shown in order to explain the image criteria scale.

CFF measurements were repeated three times in ascending and three times in descending mode for each subject. In ascending mode, the stimulus frequency started from 0 Hz and increased with 1 Hz interval until the subject started to see as a continuous stimuli, whereas in the descending mode, initial frequency was set around 60 Hz and decreased with an interval of 1 Hz until the subject indicated that the stimuli started to flicker. Average of six measurements was recorded as a critical flicker frequency of that individual. Using a questionnaire, subjects were asked to answer basic questions about their age, usage of corrective glasses or lenses, computer usage in a daily basis, average sleep duration, the sleep duration of the previous night before the experiment as well as using Likert-scale they rated between 1 (none) and 10 (definitely) to the questions before and also after the experiment like itchy eyes, burning eyes, pain around the eyes, headache, double vision which are some basic symptoms of eye fatigue.

During the first 10 min of image assessment session and the last 10 min., eye blinks of the subjects were recorded with a webcam in order to count their amount of eye blink after the experiment.

In total, 400 images were shown to evaluate with a limited time of 10 seconds for each image which took 66 minutes for one session. During the experiment, subjects were not allowed to interrupt the images. After the experiment, again the CFF were measured and also the symptoms related to eye fatigue part of subjective test was answered.

The experiment was repeated with the same subject at different ambient light levels and there was at least one week apart between two sessions for the same subject.

2.3 Measurement Equipment and Methods

2.3.1 CFF

Measuring critical flicker frequency requires a specific device which mainly consists of a processor, display, light and rotary button. Arduino can be used for basic projects as a microprocessor, to show the current frequency value of the flicker of LED, an LCD display should be used, in order to adjust the frequency value, a rotary encoder can be used for both increments and decrements mode as well the device can be utilized with two additional potentiometer, which one is responsible for brightness and the other one responsible for the contrast of the screen. The final product is shown as in figure 2.5.

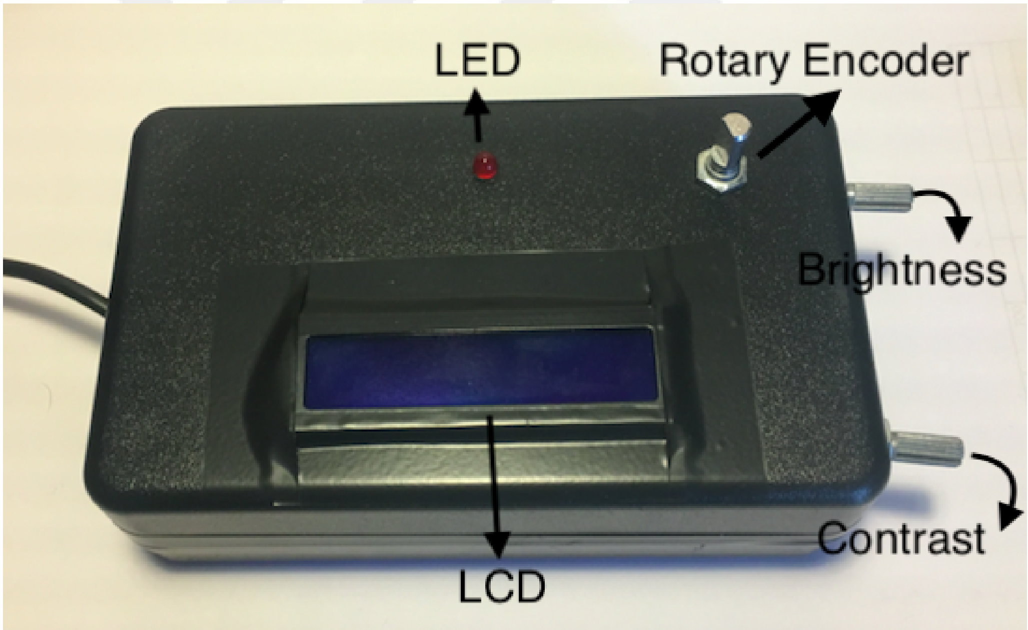


Figure 2.5 CFF device.

2.3.1.1 Arduino. Arduino is a tiny board which is programmable and allows to process inputs and outputs going to and from the chip. It uses AVR microprocessor as chip on it, and it has a crystal or oscillator as well as a linear regulator. There are lots of various types of Arduino. Depending on what type of Arduino you have, they have different number of input and output pins to connect to other circuits or sensors. The Arduino can be used to create stand-alone projects, or it can be connected to a computer in order to transfer data. Data can be processed, and control bits can also be sent through its ports. Therefore, it is a complete microprocessor with I/O flexibility.

Figure 2.6 Arduino Uno.

Uno is one of the type of Arduino, which is a good start to learn development board shown in Figure 2.6. It is based on the ATmega328, which has 14 digital input/output pins (6 of them used for PWM), 6 analog inputs, and a 16 MHz ceramic resonator. Table 2.2 gives the specs for Arduino Uno.

The microprocessor's code of this project is written in C++ language using Arduino IDE, which is an open-source environment allows to write code and upload it to the board. It is easy to learn environment to do lots of projects and it is compatible with all operating system. Most of programming platforms included Arduino IDE could use libraries which are very crucial to provide extra functionality and make writing the code easier.

Table 2.2
Specs for Arduino Uno.

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14(of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	32kB (ATmega328) of which 0.5 used by bootloader.
SRAM	2KB (ATmega328)
EEPROM	1 KB(ATmega328)
Clock Speed	16MHz

2.3.1.2 LCD. Liquid crystal display (LCD) is a flat panel display which is utilized by lots of electronic devices. It operates by light modulating characteristic of liquid crystals and It has a backlight and the brightness and contrast could be adjusted. In this device, 16x2 LCD is used to display current stimulus frequency. 16 x 2 means that the used LCD has two lines and 16 characters per line as shown in Figure 2.7.

Figure 2.7 16 x 2 LCD.

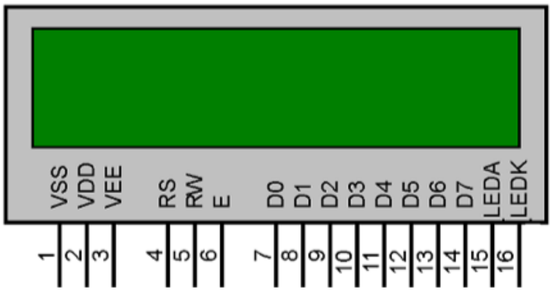


Figure 2.8 LCD pin-outs.

The LCD that is used, has 6 pins to talk to Arduino; RS, E, D7, D6, D5, D4 and all the pin-outs are shown in the figure 2.8 other pins are used to power up the LCD as well for contrast and brightness adjustments. Figure 2.9 shows that the wiring diagram between Arduino Uno and LCD.

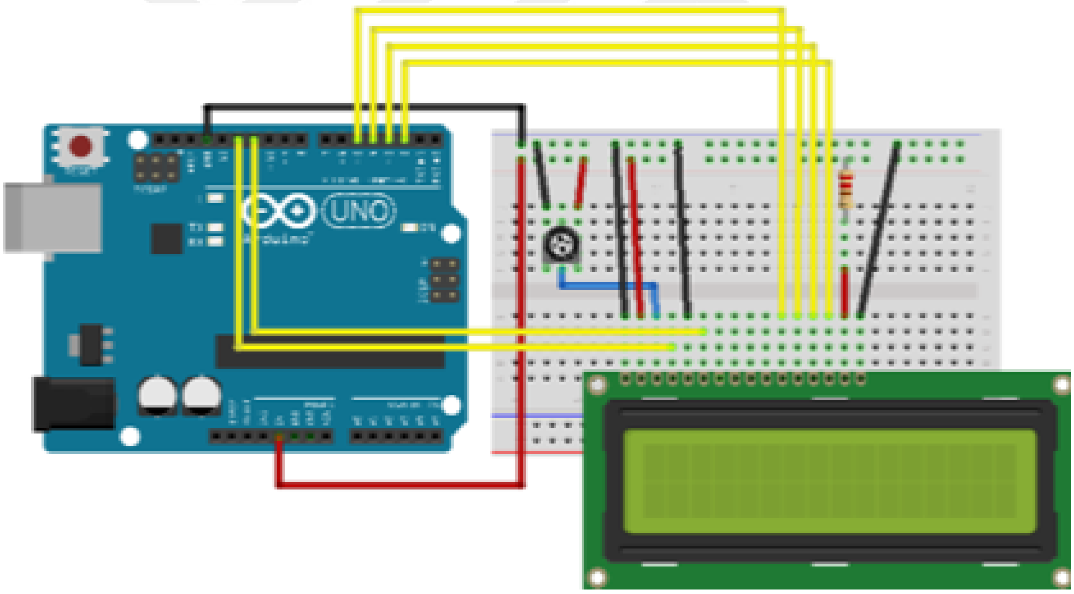


Figure 2.9 Wiring diagram between Arduino Uno and LCD.

2.3.1.3 Rotary Encoder. In order to transform angular motion into electrical signal, rotary encoders are used. There are several types of rotary encoder based on the requirements. It has two output signals which is shown in figure 2.11. When the encoder starts to rotate, the output signals are altered and one of them leads to another which is detectable by a microprocessor in order to determine rotation.

Figure 2.10 Rotary encoder.

Initially, both of the output signals are in the state "HIGH"; however, when the motion starts, one of them falls to state "LOW" first, which is followed by the other output with a lag. With implementation of the code, microprocessor is able to determine the direction of the rotation based on the signal changes. Since the rotary motion is endless, a capacitor should be used in order to reduce noise and also to make the motion detection more precise by microprocessor.

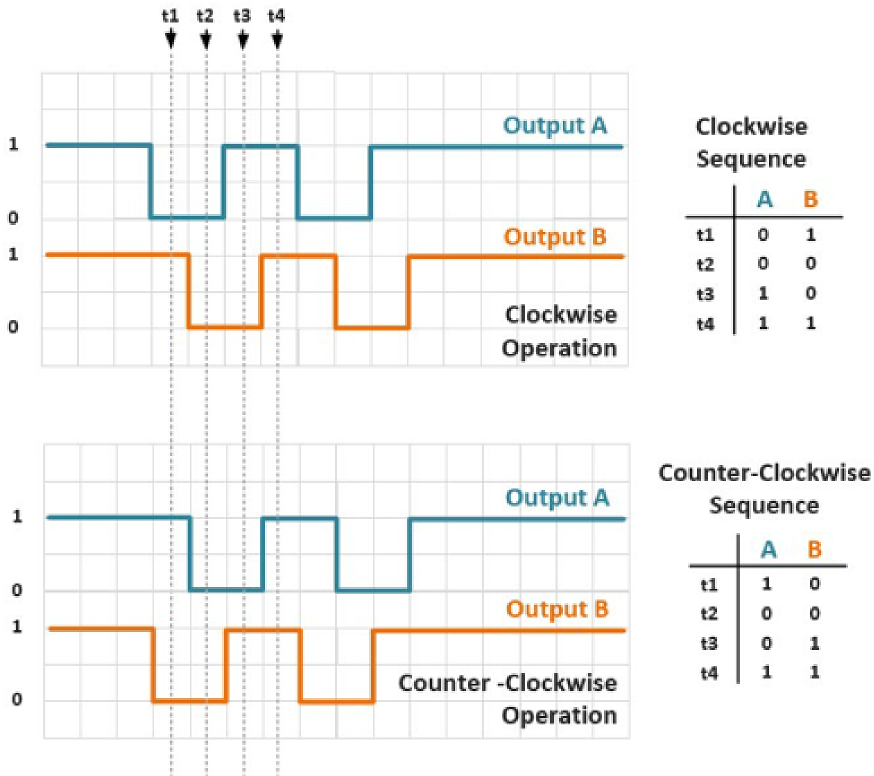


Figure 2.11 Rotary encoder working principle.

2.3.1.4 Calibration of CFF Device. After the successful assembling of all the parts of the CFF device, calibration of the device was checked using Fluke 115 model multimeter (Figure 2.12), which has a capability of measuring frequency of the voltage. Measurement was taken by connecting the terminals of the multimeter instead of LED terminals, so that the multimeter was able to read the frequency of signal, which is actually powered on the LED. Calibration was checked between the set values 20 Hz and 65 Hz with 5 Hz increments, and also for the repeatability test, 35, 40 and 45 Hz was used. Results of the calibration check is shown in table 2.3 and 2.4.

Figure 2.12 Fluke 115 multimeter.

As shown in table 2.3 and 2.4, the difference between the set value and measured value is 0.02 Hz in both types of measurements, therefore the results confirmed that the CFF device is calibrated.

Table 2.3
Calibration check of CFF device between 20 Hz and 65 Hz.

Set Value (Hz)	Measured Value (Hz)	Difference (Hz)
20	19,99	0,01
25	24,99	0,01
30	29,98	0,02
35	34,98	0,02
40	39,98	0,02
45	44,97	0,03
50	49,97	0,03
55	54,97	0,03
60	59,97	0,03
65	64,96	0,04
Average of differences (Hz)		0,024

Table 2.4
Calibration check of repeatablity of CFF device.

	Set Value (Hz)		
Number of Measurements	35	40	45
1	34,98	39,98	44,98
2	34,98	39,98	44,97
3	34,99	39,98	44,97
4	34,98	39,98	44,98
5	34,98	39,98	44,98
Average	34,982	39,98	44,976
Difference	0,018	0,02	0,024
Average of differences (Hz)			0,020666667

2.3.2 Eye Blink

Behavior of the eyes of subjects can be monitored and recorded with a webcam easily. However, some of the experiments were held at dark ambient light conditions, which can cause the webcam not to capture enough light that comes from the eyes. In order to eliminate this issue, IR-LED can be used. IR-LED is a semiconductor, which releases infrared rays when exposed to electrical current.

Converting webcam's RGB led with IR-LEDs as shown in figure 2.13 and also removing the IR filter, which lays in front of the webcam's optical lenses, makes it enabled to capture IR light that emitted from the IR-LED and reflected from the eyes of subjects. Since IR-LED has wavelength range more than 900 nm, which is not visible by human eye, it does not affect the eye fatigue level.

Figure 2.13 Webcam with IR-LEDs that is used to capture eye blinks.

2.3.3 Subjective Test

To investigate the eye fatigue based on subjectivity, a questionnaire was given to the subjects. The questionnaire consists of two parts. In the first part, general questions were asked for only once such as age, sex, usage of corrective devices, average sleeping duration. Whereas, in the second part, the eye fatigue related questions were asked to answer based on their experience before and after each experiment at different ambient light settings. Subjects answered the questions using Likert-scale, which 1 means "none" and 10 means "as high as possible". The second part of the questionnaire is shown in table 2.5. Whereas the whole questionnaire that is given to subjects can be found in appendix A.

Table 2.5
Part 2 of the questionnaire.

	0 Lux		50 Lux		500 Lux	
	Before	After	Before	After	Before	After
Itchy eyes						
Burning eyes						
Irritated eyes						
Pain around the eyes						
Headache						
Heavy eyes						
Lack of focusing						
Double vision						
Color changes						
Neck soreness						

2.4 Statistical Analysis

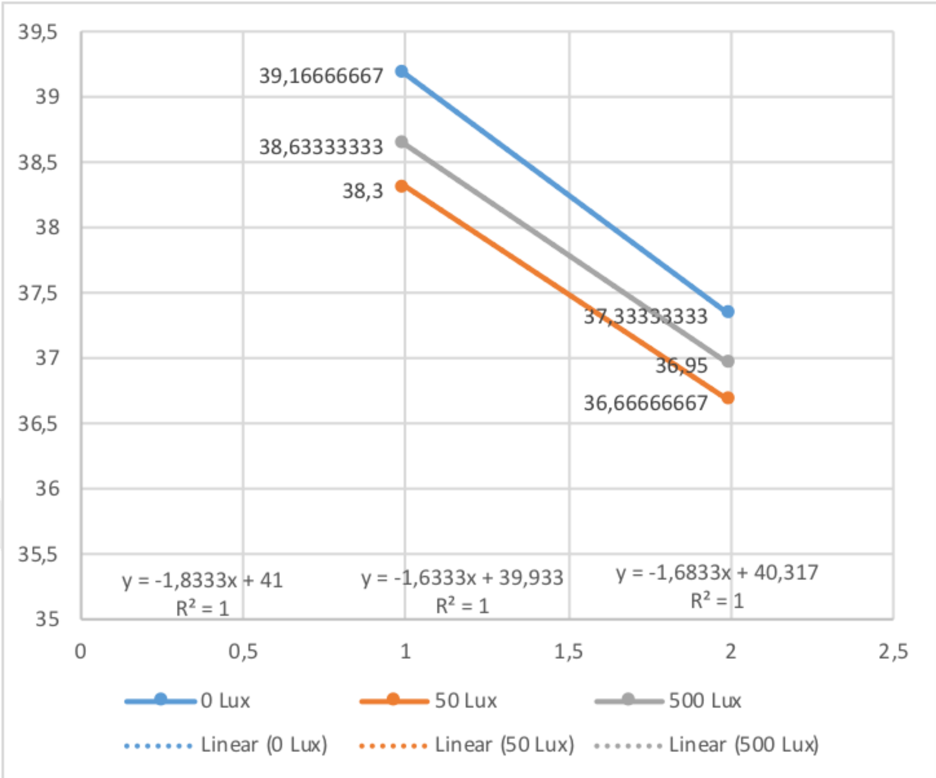
Repeated measures ANOVA was used for CFF and eye blink calculations as well as paired t-test was used in order to compare the statistically significant results. Only for the CFF case, one-tailed paired t-test was used because there was only one direction which was the after measurements should always be lower than the before measurements. Since the subjective test contains nominal data, Friedman statistics and Wilcoxon signed rank test was used. The percentages that are shown in table of data for each methods were also calculated which are represent the decreseament of the before value in percentage. Finally, in order to investigate the relation between the measurements and sleep duration, Pearson Correlation Coefficient was calculated and Repeated Measure Correlation [18] analysis was performed. Repeated measure correlation analysis were performed using "rmcorr" package in R statistical language and all the other statistical analyses were performed using SPSS version 25 and confidence interval was 95% for all statistical tests.

3. RESULTS

CFF measurements that are taken before and after the image evaluation task is given in table 3.1. Without performing any statistical analysis, graphical results in table 3.1 show that 0 Lux has the highest difference (-1.83 Hz) following by 50 and 500 Lux whereas 50 Lux and 500 Lux have almost equal difference (-1.63 Hz and -1.68 Hz respectively).

Table 3.1
Before and after CFF measurements in Hz.

	0 Lux		50 Lux		500 Lux	
	Before	After	Before	After	Before	After
Subject 1	34,5	30,33333	30,58333	29,5	35,75	31,66667
Subject 2	33,58333	33,08333	35,25	33,91667	35,16667	34,83333
Subject 3	47,66667	45,58333	44,33333	43	41,83333	38,91667
Subject 4	40,91667	39,91667	43,16667	40,33333	42,41667	41,91667
Subject 5	39,16667	37,75	38,16667	36,58333	38	37,41667
	AVERAGE					
	39,16667	37,33333	38,3	36,66667	38,63333	36,95
	DIFFERENCES					
	-1,8333 (4,68%)		-1,6333(4.26%)		-1,68333(4.35%)	



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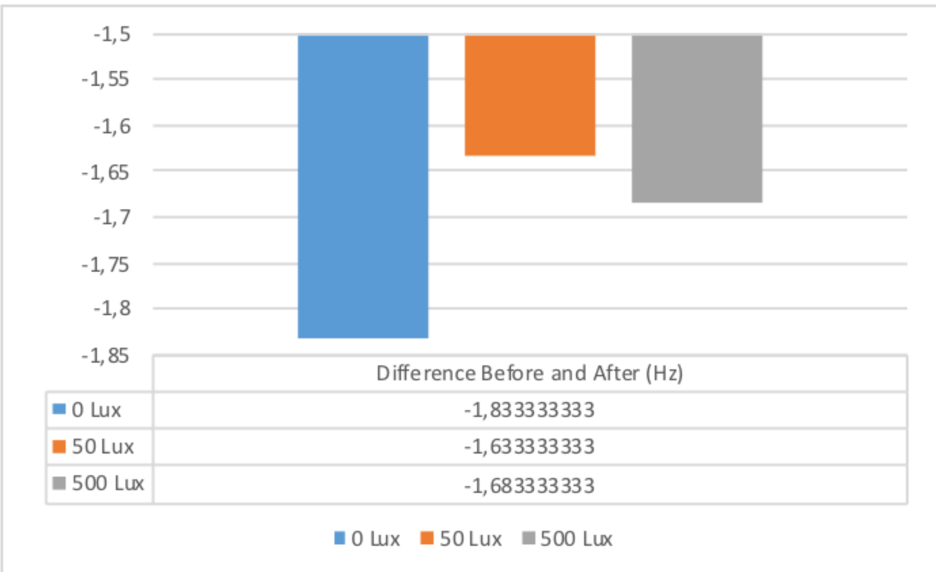


(b)

Figure 3.1 Graphical results of CFF measurements. (a) Difference between before and after CFF measurements. (b) Difference as bar graph.

Since CFF was measured before and after the visual task, paired t-test could be used for each ambient light in order to find out whether the eye fatigue is present under those light levels separately. As seen from figure 3.1, there is only one possible direction which is the CFF measurement will be always lower in after case, so one-tailed significance value could be used. Repeated measures ANOVA was used to compare different ambient light levels to each other in terms of eye fatigue. Descriptive statistics and the results of paired t-test and ANOVA are given in table 3.3 - 3.6.

Table 3.2
Before and after differences of CFF measurements for repeated measures ANOVA.

	0 Lux	50 Lux	500 Lux
Subject 1	-4,16667	-1,08333	-4,08333
Subject 2	-0,5	-1,33333	-0,33333
Subject 3	-2,08333	-1,33333	-2,91667
Subject 4	-1	-2,83333	-0,5
Subject 5	-1,41667	-1,58333	-0,58333

Table 3.3
Descriptive statistics of repeated measures ANOVA for CFF.

	Mean	Std. Deviation	N
0 Lux	-1.83	1.425	5
50 Lux	-1.63	0.694	5
500 Lux	-1.68	1.71	5

Table 3.4
Repeated measures ANOVA statistics results for CFF.

	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Lux	0.111	2	0.055	0.039	0.962	0.054
Error (Lux)	11.460	8	1.43			

Table 3.5
Descriptive statistics of paired t-test for CFF.

		Mean	N	Std. Deviation	Std. Error Mean
0 Lux	Before	39.16	5	5.66	2.53
	After	37.33	5	5.96	2.66
50 lux	Before	38.29	5	5.67	2.53
	After	36.66	5	5.30	2.37
500 Lux	Before	38.63	5	3.36	1.50
	After	36.94	5	3.90	1.75

Table 3.6
Paired t-test results for CFF measurements.

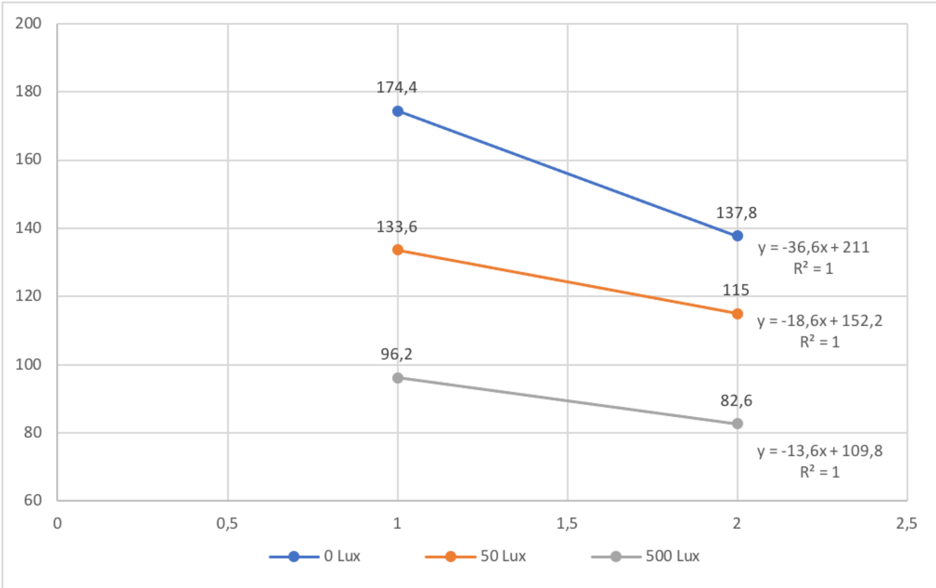
				95% Confidence Interval of the difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig.
0 Lux	1.83	1.429	0.639	0.057	3.606	2.866	4	0.023
50 Lux	1.63	0.692	0.309	0.771	2.492	5.269	4	0.003
500 Lux	1.68	1.713	0.766	-0.441	3.813	2.200	4	0.046

According to repeated measures ANOVA results (Table 3.4); there is no significant difference between the three ambient light levels in terms of eye fatigue ($F(2,8) = 0.039$; $p=0.962$). Paired t-test results in table 3.6 shows that there is significant difference before and after measurements for 0 Lux, 50 Lux, and 500 Lux within themselves. ($p = 0.023, 0.003, 0.046$ respectively.)

Table 3.7 provides the eye blink counts for the first 10 min. of image evaluation task and the last 10 min. As can be seen from figure 3.2, amount of eye blink is decreased more when the ambient light is set to 0 Lux (-36.6 blinks) which is followed by 50 and 500 Lux (-18.6 and -13.6 blinks respectively). To investigate the eye fatigue levels among the different light levels, repeated measures ANOVA was used and also to show that the eye fatigue is present under each different light levels which means there is significantly difference between the first 10 min. and last 10 min., paired t-test was used to confirm. The results obtained from the statistical analysis are given in tables 3.8 - 3.13.

Table 3.7
First and last 10 minutes of eye blink count.

	0 Lux		50 Lux		500 Lux	
	First 10 min.	Last 10 min.	First 10 min.	Last 10 min.	First 10 min.	Last 10 min.
Subject 1	297	235	209	172	123	98
Subject 2	187	173	219	215	141	128
Subject 3	109	48	56	26	52	41
Subject 4	127	84	55	50	76	63
Subject 5	152	149	129	112	89	83
	AVERAGE					
	174.4	137.8	133.6	115	96.2	82.6
	DIFFERENCES					
	-36.6 (20.9%)		-18.6 (13.92%)		-13.6 (14.1%)	



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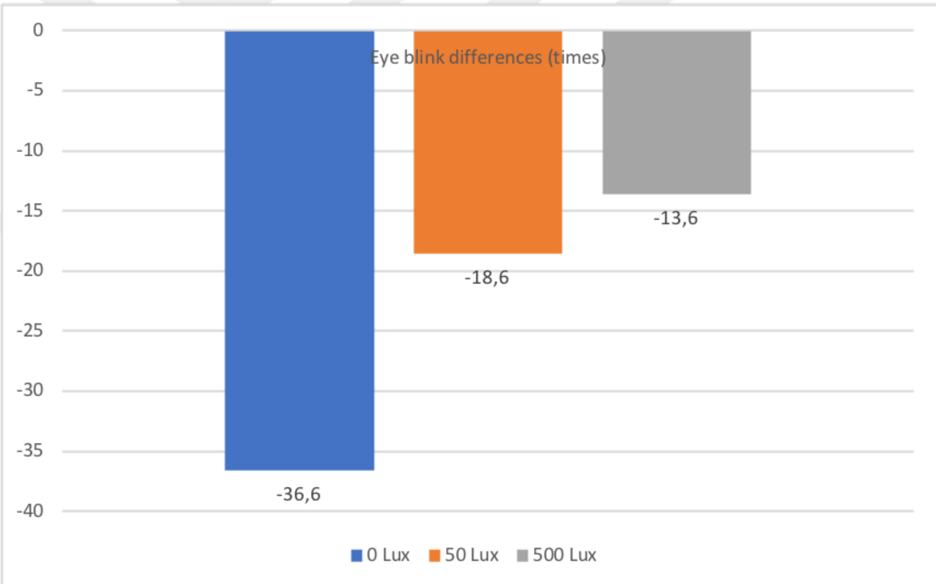


(b)

Figure 3.2 Graphical results of eye blink counts. (a) Difference between before and after for eye blink counts. (b) Difference as bar graph.

Table 3.8
Before and after differences of eye blink count for repeated measures ANOVA.

	0 Lux	50 Lux	500 Lux
Subject 1	-62	-37	-25
Subject 2	-14	-4	-13
Subject 3	-61	-30	-11
Subject 4	-43	-5	-13
Subject 5	-3	-17	-6

Table 3.9
Descriptive statistics of repeated measures ANOVA for eye blink.

	Mean	Std. Deviation	N
0 Lux	-36.6	27.02	5
50 Lux	-18.6	14.74	5
500 Lux	-13.6	6.98	5

Table 3.10
Repeated measures ANOVA statistics results for eye blink count.

	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Lux	1463.33	2	731.66	3.914	0.065	0.531
Error (Lux)	1495.33	8	186.91			

Table 3.11
Pairwise comparison of repeated measures ANOVA for eye blink count.

		Pair 1	Pair 2	Pair 3
		0 Lux - 50 Lux	0 Lux - 500 Lux	50 Lux - 500 Lux
	Mean	-18.00	-23.00	-5.00
	Std. Deviation	20.65	23.09	12.70
	Std. Error Mean	9.23	10.32	5.68
95% confidence interval of the Difference	Lower	-43.64	-51.67	-20.77
	Upper	7.64	5.67	10.77
	t	-1.949	-2.227	-0.880
	df	4	4	4
	Sig.	0.061	0.045	0.214
	Benferonni Adjusted p values	0.183	0.135	0.643

Table 3.12
Descriptive statistics of paired t-test for eye blink count.

		Mean	N	Std. Deviation	Std. Error Mean
0 Lux	First 10 min.	174.40	5	74.52	33.32
	Last 10 min.	137.80	5	73.77	32.99
50 lux	First 10 min.	133.60	5	79.37	35.49
	Last 10 min.	115.00	5	79.69	35.63
500 Lux	First 10 min.	96.20	5	35.84	16.02
	Last 10 min.	82.60	5	33.21	14.85

Table 3.13
Paired t-test results for eye blink count.

		0 Lux	50 Lux	500 Lux
	Mean	36.60	18.60	13.60
	Std. Deviation	27.02	14.74	6.98
	Std. Error Mean	12.085	6.592	3.124
95% Confidence Interval of the Difference	Lower	3.045	0.296	4.926
	Upper	70.15	36.90	22.27
	t	3.028	2.821	4.353
	df	4	4	4
	Sig.	0.019	0.024	0.006

The result of repeated measures ANOVA from table 3.10 shows that there is a trend to be significantly different between the ambient light levels. ($F(2,8) = 3.914$; $p = 0.065$). This almost significant differences mostly come from the difference between 0 lux and 50 lux as well as 0 lux and 500 lux whereas the p-values are 0.061 and 0.045 respectively. According to pairwise comparison, there is no significant difference in the amount of blinks between the 50 Lux and 500 Lux ($p = 0.214$). Due to the sample size issues, Benferonni adjusted p-values could not be evaluated in order to avoid conservative environment of Benferonni. Likewise, the CFF measurements, eye blink counts also indicates that at each ambient light levels eye fatigue was present. The results of paired t-test which is shown in table 3.13 also confirmed that there is a significant difference between before and after counts for 0 Lux, 50 Lux, and 500 Lux within themselves ($p = 0.019$, 0.024, 0.006 respectively).

During the experiment, Subject 5 suffered from dry eyes more than the others. Since people tend to blink more in order to fight back with the dryness, subject 5 was excluded from the results of Eye Blink measurements in order to investigate the others eye fatigue levels. Tables 3.14 - 3.17 shows the results where subject 5 was excluded.

Table 3.14

Descriptive statistics of repeated measures ANOVA for eye blink count without subject 5.

	Mean	Std. Deviation	N
0 Lux	-45.00	22.43	4
50 Lux	-19.00	16.99	4
500 Lux	-15.50	6.40	4

Table 3.15

Repeated measures ANOVA statistics results for eye blink count without subject 5.

	Sum of Squares	df	Mean Square	F	Sig.	Observed Power
Lux	2078.00	2	1039.00	8.075	0.020	0.789
Error (Lux)	772.00	6	128.66			

Table 3.16

Pairwise comparison of repeated measures ANOVA for eye blink count without subject 5.

		Pair 1	Pair 2	Pair 3
		0 Lux - 50 Lux	0 Lux - 500 Lux	50 Lux - 500 Lux
	Mean	-26.00	-29.50	-3.50
	Std. Deviation	11.91	20.72	14.15
	Std. Error Mean	5.95	10.36	7.07
95% Confidence Interval of the Difference	Lower	-44.961	-62.483	-26.022
	Upper	-7.038	3.483	19.022
	t	-4.364	-2.846	-0.495
	df	3	3	3
	Sig.	0.011	0.032	0.327
	Benferonni Adjusted p values	0.033	0.096	0.982

Table 3.17
Paired t-test results for eye blink count without subject 5.

		0 Lux	50 Lux	500 Lux
	Mean	45	19	15.50
	Std. Deviation	22.43	16.99	6.40
	Std. Error Mean	11.217	8.495	3.201
95% Confidence Interval of the Difference	Lower	9.300	-8.035	5.311
	Upper	80.699	46.035	25.688
	t	4.012	2.237	4.841
	df	3	3	3
	Sig.	0.014	0.055	0.006

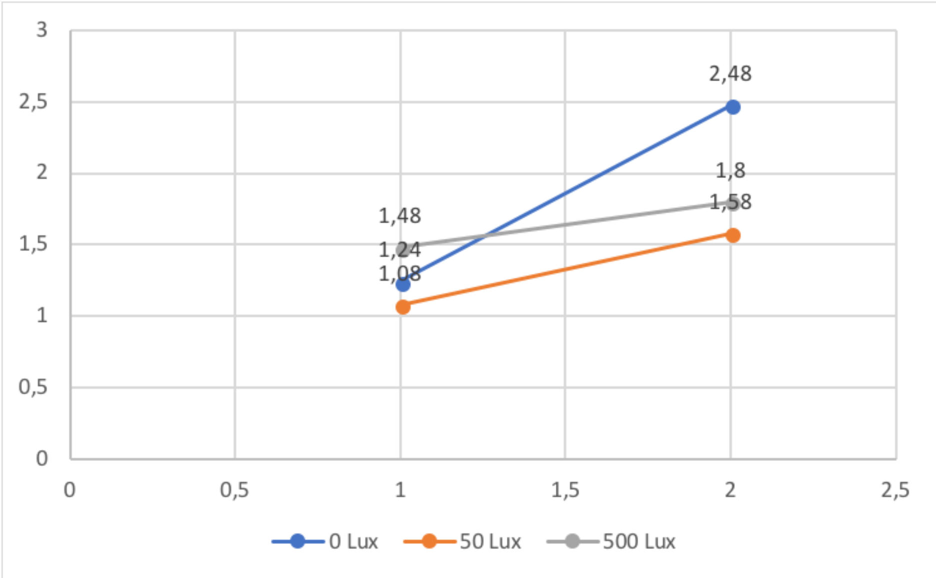
Table 3.15 presents that there is a significant difference between the ambient light levels in terms of eye fatigue. ($F(2,6) = 8.075$; $p = 0.020$). Without performing any adjustment like Benferonni due to the same reasons, pairwise comparison from table 3.16 provides that there is a significant difference between the ambient light levels 0 Lux and 50 Lux ($p = 0.011$) and also between the ambient light levels 0 Lux and 500 Lux ($p = 0.032$), unlike the 50 Lux and 500 Lux comparison which have a p-value as high as 0.327. Paired t-test statistics results in table 3.17 shows that the eye fatigue was present during the experiment under ambient light 0 Lux and 500 Lux ($p= 0.014$, 0.006 respectively), whereas there is a almost significant difference between before and after eye blink count at 50 Lux ($p = 0.055$).

For the subjective test, mean points that the subjects gave are presented in Table 3.18. From figure 3.3 there is huge increase between before and after score for 0 Lux (1.24 points) compared to other levels (0.5 points and 0.32 points respectively for 50 Lux and 500 Lux). Based on the differences of the subjective test, 50 Lux and 500 Lux create almost the same eye fatigue score.

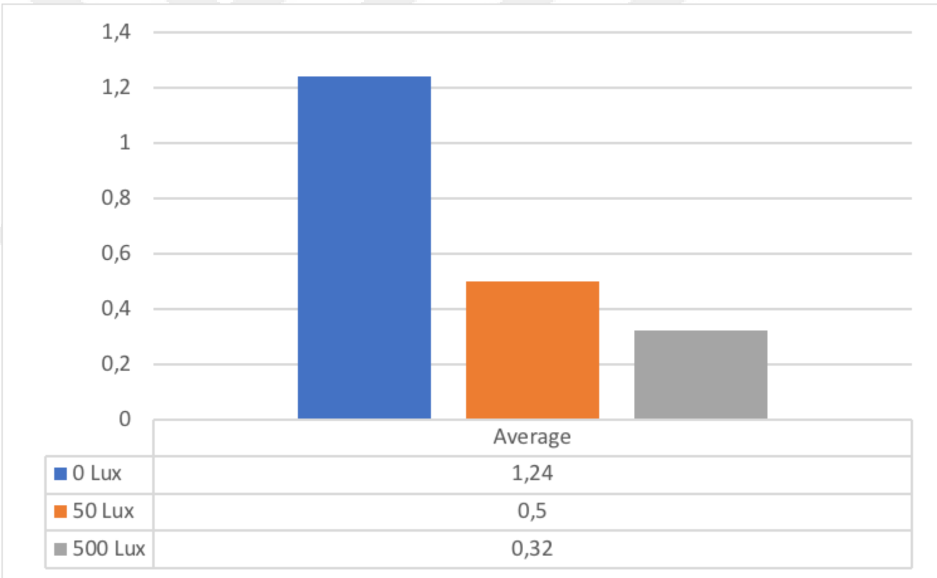
Table 3.18
Average of before and after answers of subjective test.

	0 Lux		50 Lux		500 Lux	
	Before	After	Before	After	Before	After
Subject 1	1	1.8	1.2	1.5	2.6	2.9
Subject 2	1.9	4	1.1	1.3	1.7	1.7
Subject 3	1	2.3	1	2.1	1	1.6
Subject 4	1	2.5	1	1.7	1	1.6
Subject 5	1.3	1.8	1.1	1.3	1.1	1.2
	AVERAGE					
	1.24	2.48	1.08	1.58	1.48	1.8
	DIFFERENCES					
	1.24 (100%)		0.5 (46.2%)		0.32 (21.62%)	

Since the Likert scale is nonparametric, Friedman Test Statistics and Wilcoxon Signed Rank Test were used to perform statistical analysis instead of Repeated Measures ANOVA and Paired t-test. The results are provided in table 3.19 - 3.23.



(a)



(b)

Figure 3.3 Graphical results of subjective test. (a) Subjective test average differences. (b) Graphical results of subjective test.

Table 3.19
Differences for Friedman test statistics.

	0 Lux	50 Lux	500 Lux
Subject 1	0.8	0.3	0.3
Subject 2	2.1	0.2	0
Subject 3	1.3	1.1	0.6
Subject 4	1.5	0.7	0.6
Subject 5	0.5	0.2	0.1

Table 3.20
Mean ranks of subjective test.

0 Lux	3.90
50 Lux	1.90
500 Lux	1.10

Table 3.21
Friedman test statistics results.

N	5
Chi - Square	9.579
df	2
Sig.	0.008

Table 3.22
Pairwise comparison of Friedman results using Wilcoxon signed rank test.

	Z	Sig.
0 Lux - 50 Lux	-2.023	0.043
0 Lux - 500 Lux	-2.023	0.043
50 Lux - 500 Lux	-1.841	0.066

Table 3.23
Wilcoxon signed rank test results.

	Z	Sig.
0 Lux	-2.023	0.043
50 Lux	-2.032	0.043
500 Lux	-1.841	0.066

From table 3.21, Friedman test shows that there is a significant difference between ambient light. (Chi-square = 9.579; p = 0.008). Without using any adjustment like Benferonni, pairwise comparison from table 3.22 indicates that there is a significant difference between 0 and 50 Lux as well as between 0 and 500 Lux (p=0.043 for both). However, there is no significant difference between 50 and 500 Lux (p=0.66). Table 3.23 shows significance between the before and after score for each ambient light individually. Wilcoxon signed rank test indicated that there is significant difference between before and after score for 0 and 50 lux (p= 0.043 for both); however, there is no significant difference for 500 Lux (p = 0.066).

To find out the correlation between the tests and sleep duration, Pearson correlation statistics was used. The correlation between the before values of measurement methods were investigated as well as their correlation with sleep durations. Same analysis were performed using after values. The differences between the before and after values and their relation with sleep duration were also investigated using the same analysis.

Table 3.24 presents the pearson correlation coefficient and significance value between the before and after measurements differences of eye fatigue measurement methods. As it is easily seen from the Table 3.24, there is no significant correlation between the differences of three different eye fatigue test.

In order to investigate the relation between the eye fatigue measurement methods and the sleep duration, subjects were asked to answer the question about their sleep duration the night before each session. Based on the answers, Subjects tend to sleep

6.8 hours (range 6h-8h) in average generally and the average sleep duration previous night before the experiment is 6.73 hours (range 4.5h - 8h). Table 3.25 presents the sleep duration in hours of subjects the night before each experimental session whereas, Table 3.26 provides the correlation between the tests and sleep duration. According to results there is no significant correlation between the sleep duration and the tests.

Table 3.24
Correlations between the difference of CFF, eye blink and subjective test.

			Subjective Test			CFF		
			0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux
CFF	0 Lux	Pearson Coeff.	0.581					
		Sig.	0.304					
	50 Lux	Pearson Coeff.		-0.252				
		Sig.		0.683				
	500 Lux	Pearson Coeff.			-0.337			
		Sig.			0.579			
Eye Blink	0 Lux	Pearson Coeff.	0.039			0.675		
		Sig.	0.950			0.211		
	50 Lux	Pearson Coeff.		-0.228			-0.621	
		Sig.		0.712			0.264	
	500 Lux	Pearson Coeff.			-0.095			0.712
		Sig.			0.879			0.178

Table 3.25
Sleep duration the night before the each experiment session (hours).

	0 Lux	50 lux	500 Lux
Subject 1	4.5	5	5.5
Subject 2	6	6	6
Subject 3	8	7	8
Subject 4	8	8	7
Subject 5	8	8	6

Table 3.26
Correlation between the sleep duration and the eye-fatigue tests.

			CFF			Eye Blink			Subjective Test		
			0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux
Sleep Durations	0 Lux	Pearson Coeff.	0.603			0.253			-0.045		
		Sig.	0.282			0.681			0.942		
	50 Lux	Pearson Coeff.		-0.705			0.486			0.292	
		Sig.		0.184			0.406			0.633	
	500 Lux	Pearson Coeff.			-0.012			0.412			0.766
		Sig.			0.984			0.491			0.131

Correlations between the before values of CFF, Eye Blink, and Subjective Test and as well as their correlation with sleep durations are given in Table 3.27. At 50 lux, all the tests were correlated with each other significantly. Correlation between the CFF and Subjective Test was at the p = 0.003 level, whereas there is also significantly correlation between CFF and Eye Blink (p = 0.018). Subjective Test and Eye Blink almost significantly correlated at 50 Lux (p = 0.054) and significantly correlated at 500 Lux (p = 0.025). At 0 Lux; sleep durations and Eye Blink values were also correlated significantly (p = 0.012).

Table 3.27
Correlations between the values of before the experiment measurements and sleep durations.

			Subjective Test			CFF			Eye Blink		
			0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux
CFF	0 Lux	Pearson Coeff.	-0.567								
		Sig.	0.319								
	50 Lux	Pearson Coeff.		-0.980							
		Sig.		0.003							
	500 Lux	Pearson Coeff.			-0.764						
		Sig.			0.133						
Eye Blink	0 Lux	Pearson Coeff.	0.040			-0.759					
		Sig.	0.950			0.137					
	50 Lux	Pearson Coeff.		0.872			-0.939				
		Sig.		0.054			0.018				
	500 Lux	Pearson Coeff.			0.742			-0.925			
		Sig.			0.151			0.025			
Sleep Durations	0 Lux	Pearson Coeff.	-0.192			0.760			-0.954		
		Sig.	0.757			0.136			0.012		
	50 Lux	Pearson Coeff.		-0.733			0.784			-0.772	
		Sig.		0.159			0.117			0.126	
	500 Lux	Pearson Coeff.			-0.724			0.864			-0.851
		Sig.			0.167			0.059			0.068

Table 3.28 shows the correlation values between the after values of CFF, Eye Blink, and Subjective Test and also their correlation between the sleep duration the night before. Only correlation occurred between CFF and Eye Blink after measurements at 0 lux (p = 0.006) and at 50 lux (p = 0.05). There is no significant correlation between the sleep duration and the tests, however there is a trend to be significant correlation between CFF and sleep duration and between Eye blink and sleep duration at 500 lux (p = 0.059 and 0.068 respectively).

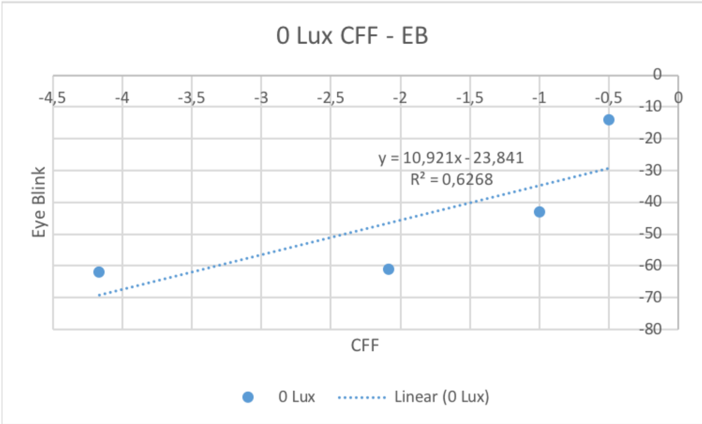
Table 3.28
Correlations between the values of after the experiment measurements and sleep durations.

			Subjective Test			CFF			Eye Blink		
			0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux	0 Lux	50 Lux	500 Lux
CFF	0 Lux	Pearson Coeff.	-0.159								
		Sig.	0.799								
	50 Lux	Pearson Coeff.		0.719							
		Sig.		0.171							
	500 Lux	Pearson Coeff.			-0.721						
		Sig.			0.169						
Eye Blink	0 Lux	Pearson Coeff.	-0.019			-0.970					
		Sig.	0.976			0.006					
	50 Lux	Pearson Coeff.		-0.804			-0.879				
		Sig.		0.101			0.050				
	500 Lux	Pearson Coeff.			0.285			-0.686			
		Sig.			0.642			0.201			
Sleep Durations	0 Lux	Pearson Coeff.	-0.114			0.867			-0.871		
		Sig.	0.855			0.057			0.054		
	50 Lux	Pearson Coeff.		-0.160			0.747			-0.678	
		Sig.		0.797			0.147			0.208	
	500 Lux	Pearson Coeff.			-0.446			0.738			-0.832
		Sig.			0.451			0.155			0.081

In order to investigate the relation between the ambient light and eye fatigue, more detailed correlation analysis were performed such as Repeated measure correlation and regression analysis. Moreover, graphical analysis were performed per subject. Due to the same reason that was explained in the previous correlation analysis, subject 5 was excluded from the results. Table 3.29 shows the regression analysis between the eye fatigue measurement tests without subject 5 and graphical results are given in figure 3.4 - 3.6.

Table 3.29
Regression analysis between the eye fatigue tests.

			Eye Blink			Subjective Test		
			0 lux	50 lux	500 lux	0 lux	50 lux	500 lux
CFF	0 lux	Corr Coeff	0,791715688			0,934557689		
		R square	0,626813731			0,873398073		
		Sig.	0,208284312			0,065442311		
	50 lux	Corr Coeff		0,625055622			0,259467688	
		R square		0,390694531			0,067323481	
		Sig.		0,374944378			0,740532312	
	500 lux	Corr Coeff			0,665768099			0,212400984
		R square			0,443247162			0,045114178
		Sig.			0,334231901			0,787599016
Eye Blink	0 lux	Corr Coeff				0,931122209		
		R square				0,866988568		
		Sig.				0,068877791		
	50 lux	Corr Coeff					0,224192401	
		R square					0,050262233	
		Sig.					0,775807599	
	500 lux	Corr Coeff						0,244677262
		R square						0,059866962
		Sig.						0,755322738



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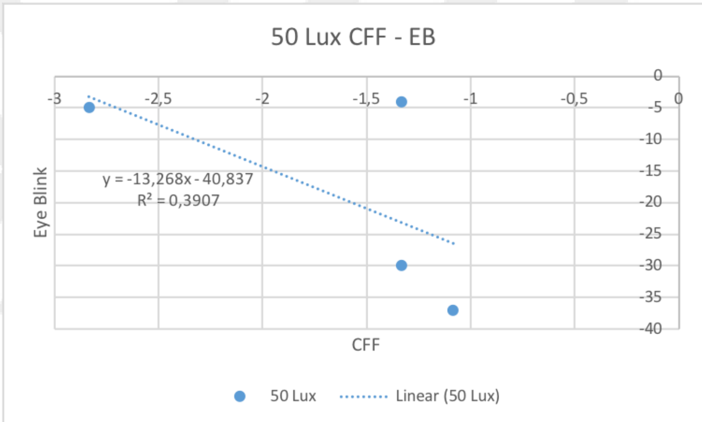

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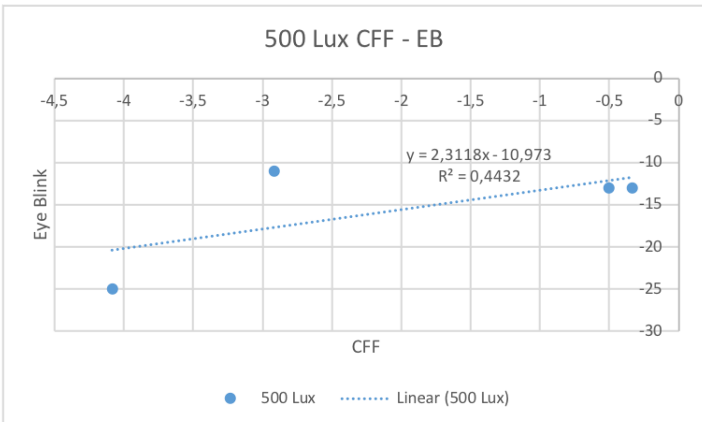
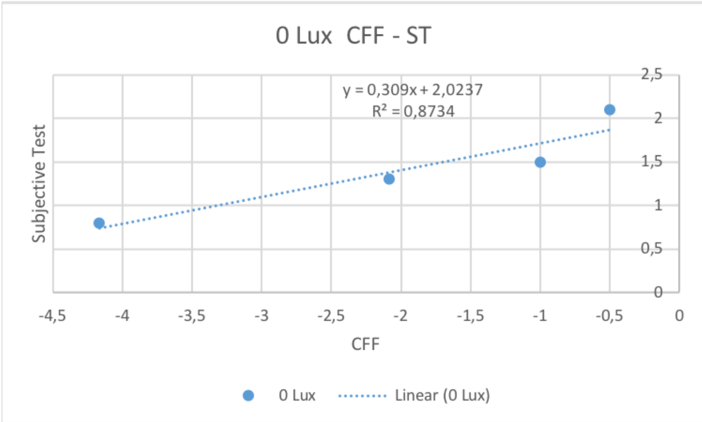
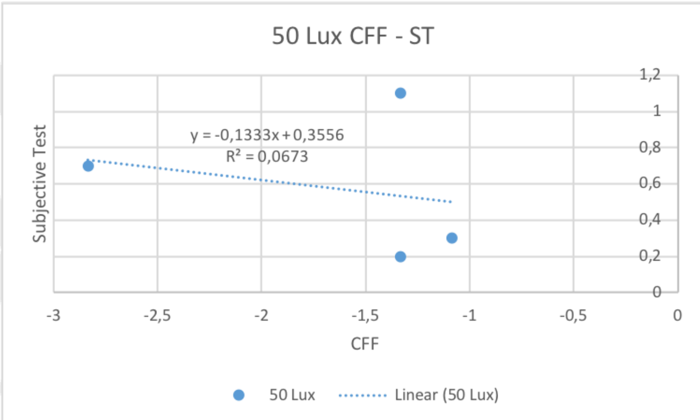


(c)

Figure 3.4 Graphical results of regression analysis of CFF and eye blink. (a) Regression analysis between CFF and eye blink at 0 lux. (b) Regression analysis between CFF and eye blink at 50 lux. (c) Regression analysis between CFF and eye blink at 500 lux.



(a)



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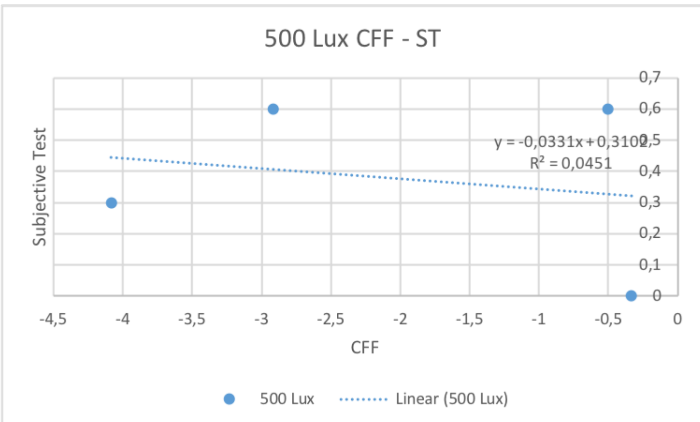
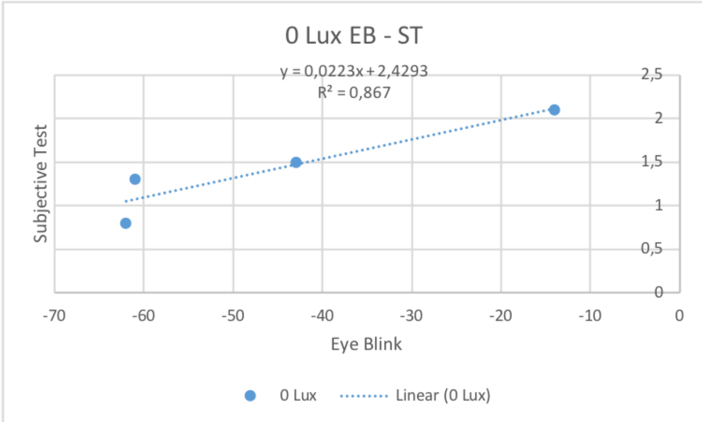


(c)

Figure 3.5 Graphical results of regression analysis of CFF and subjective test. (a) Regression analysis between CFF and subjective test at 0 lux. (b) Regression analysis between CFF and subjective test at 50 lux. (c) Regression analysis between CFF and subjective test at 500 lux.



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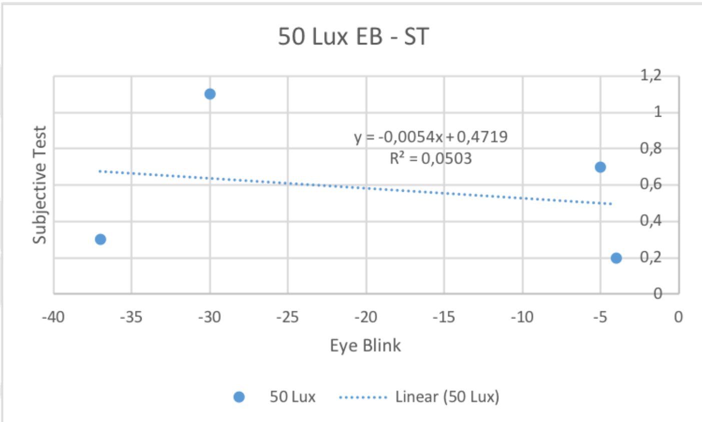

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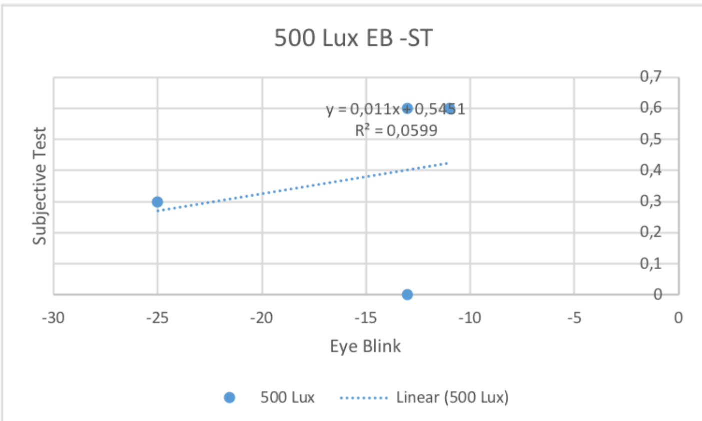


(c)

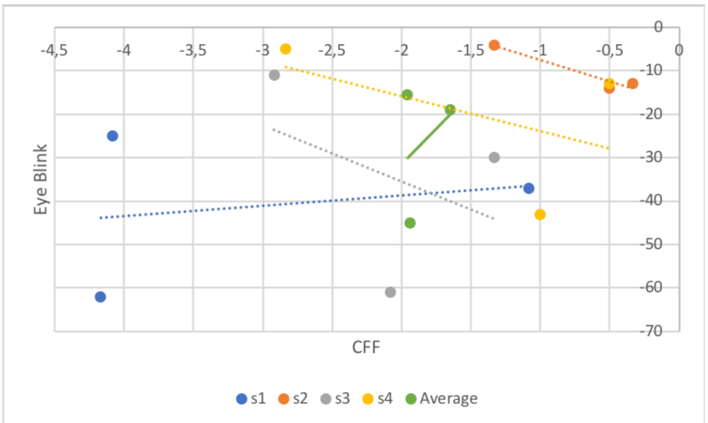
Figure 3.6 Graphical results of regression analysis of eye blink and subjective test. (a) Regression analysis between eye blink and subjective test at 0 lux. (b) Regression analysis between eye blink and subjective test at 50 lux. (c) Regression analysis between eye blink and subjective test at 500 lux.

According to Table 3.29, there is no significant correlation between the tests; however, at 0 lux CFF and Subjective Test are tend to be significantly correlated (p = 0.065) and there is a trend to be significantly correlated between Eye Blink and Subjective Test at 0 lux (p = 0.068).

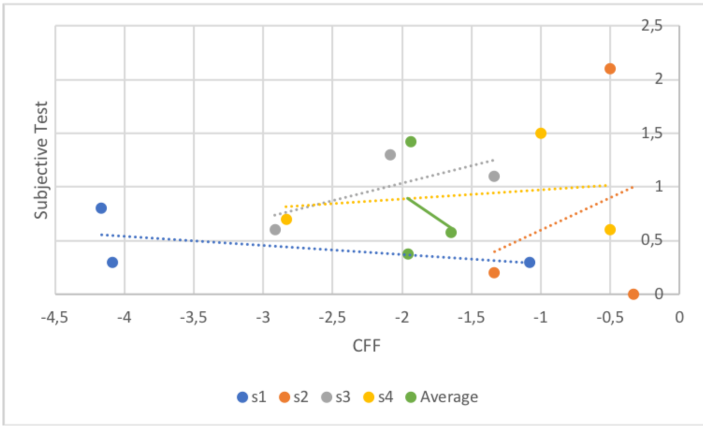
Table 3.30 shows the results of pearson correlation analysis of average values of subjects. Figure 3.7 shows the graphical results of correlation between the tests per subject and also average of subjects. There was strong correlation between the Eye blink and Subjective Test results (p = 0.045). As it is clearly seen from figures difference between before and after measurements are tend to decrease with increasing ambient light.

Table 3.30
Results of Pearson correlation analysis of average values of subjects.

	CFF - EB	CFF - ST	EB - ST
Corr Coeff.	0,347727853	0,279816947	0,997441877
R square	0,12091466	0,078297524	0,994890297
Sig.	0,77390663	0,819452446	0,045545816



(a)



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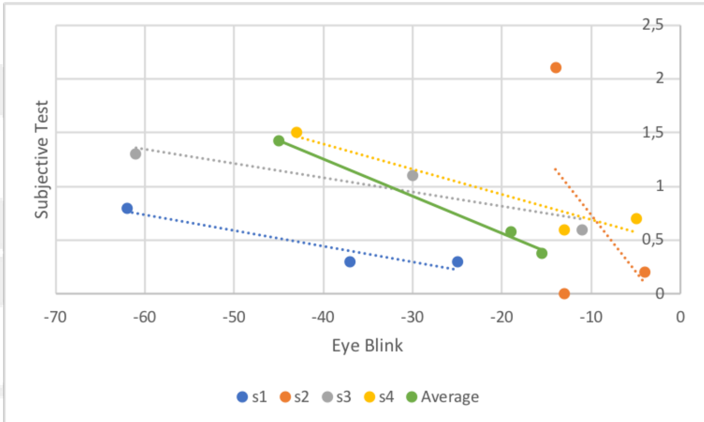


(c)

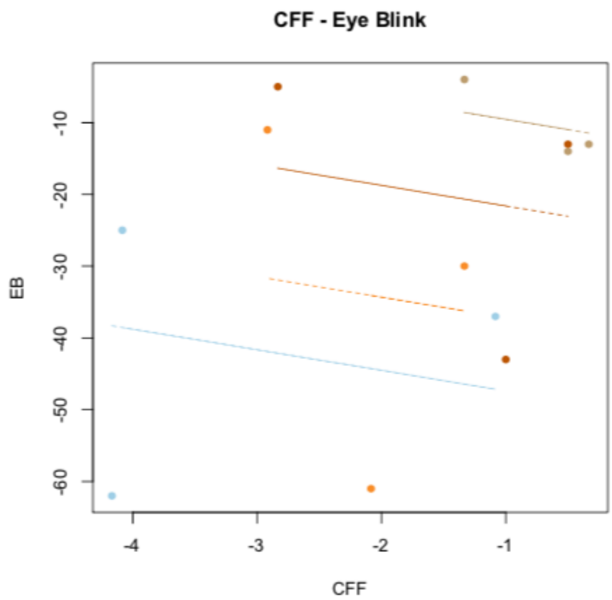
Figure 3.7 Graphical results of correlation analysis per subject at 0, 50 and 500 lux. (a) Correlation analysis between CFF and eye blink per subject at 0, 50, 500 lux. (b) Correlation analysis between CFF and subjective test per subject at 0, 50, 500 lux. (c) Correlation analysis between eye blink and subjective test per subject at 0, 50, 500 lux.

Since the measurements were taken at different ambient lighting settings on same subjects, repeated measure correlation analysis were performed using R programming language and rmcorr package. Table 3.31 shows the results of repeated measure correlation analysis.

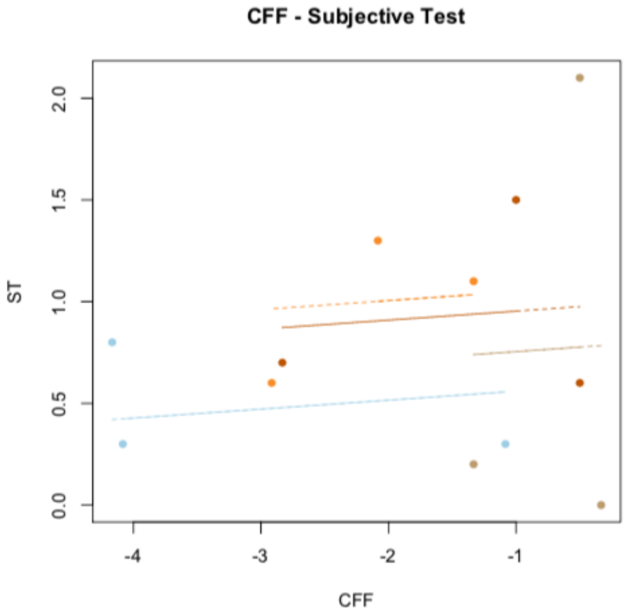
Table 3.31
Results of repeated measure correlation.

		CFF - Eye Blink	CFF - Subjective Test	Eye Blink - Subjective Test
	Corr. Coeff	-0.1783839	0.07718318	-0.5186344
	degrees of freedom	7	7	7
	p-value	0.64	0.84	0.15
95%confidence interval	upper	0.663	0.784	0.384
	lower	-0.821	-0.717	-0.914

According to repeated measure analysis (Table 3.31) there is no significant correlation between eye fatigue tests at different ambient lighting settings. Figure 3.8 shows the graphical results of repeated measure of correlation.



(a)



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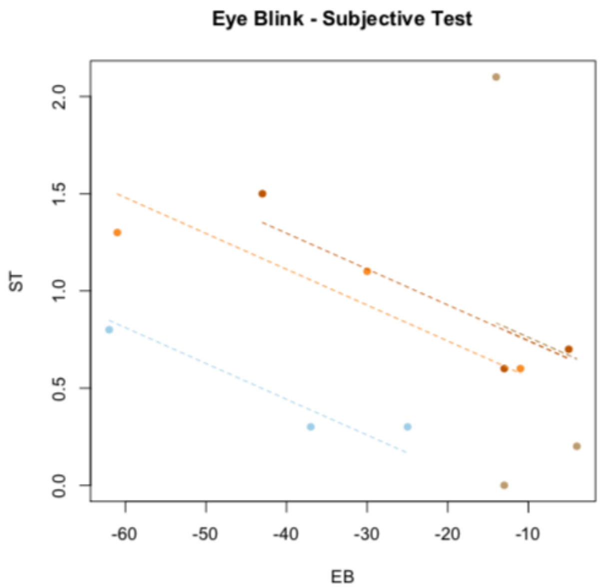

(c)

Figure 3.8 Graphical results of repeated measure correlation analysis. (a) Graphical result of repeated measure correlation between CFF and eye blink. (b) Graphical result of repeated measure correlation between CFF and subjective test. (c) Graphical result of repeated measure correlation between eye blink and subjective Test.

4. DISCUSSION AND CONCLUSION

As stated in the Introduction section, our main aim was to investigate the relation between eye fatigue and ambient light. More specifically, our aim was to study whether working in a dark environment increases eye fatigue or not and consequently, to investigate whether the radiologists, who have to work in dark environments, have more eye fatigue than the employees who are working with visual display terminals in a well-lit environment. To find out this relationship, we used in this study three different ambient lighting settings (0, 50 and 500 Lux) and three different eye-fatigue measurement methods (CFF, Eye Blink Count, Subjective Test).

As reported by Maeda et al. [14], the evidence that we found from the results of CFF measurement supports the idea that the CFF is decreased considerably when the eye fatigue is increased. Since it is physiologically impossible not to have eye fatigue after working long hours with visual terminal displays, the decrements of CFF threshold value after the image evaluation task was the result that we expected for all ambient lighting settings. However; what is surprising is the fact that, according to results of repeated measures ANOVA, there was no significant difference between amount of eye fatigue that was present under each three different ambient lighting settings that we set during the experiment. A possible explanation for this result may be the limited sample size. Given that, if we consider the absolute changes between before and after measurements, we can conclude that the eye fatigue was high at 0 lux in compare to other ambient light levels.

Considering the results of repeated measures ANOVA for eye blink tend to be significant, in order to investigate the difference between the different lighting settings we excluded subject 5 from the results due to the reason that he/she indicated that suffering eye dryness too much, especially when the ambient light was set to 50 lux, which can cause blink more to fight against dryness; however, we believed that it can also alter the results. Once we removed subject 5, although there was no change in paired t-test results for 0 and 500 lux, there was a change for 50 lux. In contrast to result of CFF measurement, Eye Blink count's results indicated that there was no eye fatigue when the ambient light was set to 50 lux. According to Chawla et al. [19] it is possible to decrease the eye fatigue by reducing the luminance difference between the background and the visual terminal display. Thus, we believed that one of the possible explanations of this result is the fact that the luminance difference between the background and visual terminal display was low in contrast to other settings. Repeated measures ANOVA results was also changed; therefore, we were able to perform pairwise comparison to find out the difference between ambient lighting settings. Pairwise comparisons led us to conclude that the tendency to be significant came from the difference between 0 - 50 lux and 0 - 500 lux, whereas there was no significant difference between 50 and 500 lux. Despite the lack of evidence in order to distinguish the difference between 50 and 500 lux, we can conclude that eye fatigue was present more at 0 lux ambient light condition.

Inevitably, there were some inaccuracies between the CFF measurements and Eye Blink counts due to the fact that eye blinks behavior depends on lots of factors such as the types of lenses used, the hours the subject was wearing the lenses before the experiment. Therefore, we believed that the CFF is more reliable. Since we measured a time interval unlike the CFF measurement, it also depends on what the subject did until the experiment because if she or he was physically tired they would tend to blink more. Unfortunately, it is impossible to eliminate all the other factors for all subject and for each ambient lighting settings, so we cannot expect that eye blink measurement and CFF fully support each other.

Since we were not able to measure the hormone levels at each ambient lighting settings, we performed a subjective test in order to find out how subjects were feeling at different ambient lights. As we expected, the results showed that the eye fatigue is not present at 500 lux unlike the other ambient lighting settings. Besides, during the image evaluation session, all subjects complained about more or less the same inconvenience in a short time of period which were severe headache and pain around the eyes for 0 lux and drowsiness for 50 lux. What is surprising is the fact that, even though there was a significant difference between the ambient lights, this significance came from the difference between 0 - 50 lux and 0 - 500 lux nonetheless there was no significant difference between 50 and 500 lux according to Friedman Statistics. Moreover; when we considered the absolute changes, it is clear to conclude that subjects felt almost three times more eye fatigue when the ambient light is set to 0 lux.

Once we consider the percentage decreasement from the before value, it is clearly seen that the changes for 50 lux and 500 lux was almost the same for CFF and Eye blink count, whereas, for the subjective test, the percentage difference between the 50 lux and 500 lux results were less in compare to 0 lux which is clarify that, according to pairwise comparison for Eye blink and Subjective test results, there was no statistically significant difference between 50 and 500 lux. Moreover, these results showed that the relationship between ambient lighting and eye fatigue is exponential rather then linear which means that the amount of eye fatigue decreases exponentially with the increase of level of ambient lighting.

Due to the fact that the experiments were performed one-week apart from each other for the same subject, we also investigated whether the sleep duration the night before had an effect on the test results. In order to do so, we also asked the subject to answer the questions related to the sleep duration and performed a correlation test. We were not able to find out a significant correlation between the before and after differences and the sleep duration which shows reliability on the test that performed on different days. Furthermore, since the eye-fatigue measurements methods that we performed were independent from each other, there was no significant correlation between those test. These results also support one of the study that is done by Maeda et al. [14] who performed pearson correlation between subjective test and CFF and found out that there was no significant correlation between CFF and subjective test either before or after or between before and and after differences in CFF and subjective test. Once we removed the subject 5 from the correlation, although there was still no significant correlation between the tests, at 0 lux however, Subjective test were tend to be significantly correlated with CFF and Eye Blink tests. Moreover; when we considered the visual graphics per subjects, we realized that the correlation between the difference between the before and after values of the eye blink and subjective test were tend to decrease in average when we increased the ambient lighting settings ($p = 0.04$). Finally, according to Bakdash et al. [18] the pearson correlation analysis may fail to give the error-free results on the repeated measure correlation analysis, thus we also performed the repeated measure correlation analysis which was proposed by Bakdash et al., which showed that there was no significant correlation between the tests.

We are aware that this study may have several significant limitations. The first one was the sample size which should be as much as large in order to distinguish ambient lighting settings from each other more precisely. The second one was the subjects were not real radiologist. Since the focus of this study was only eye-fatigue, we have doubt that using real radiologist may alter the results or provide better results, however, a study using real radiologist may provide more absolute results. Given that, another possible limitation was that all subjects were wearing contact lenses, which might have had unexpected effects on the results of eye blink count.

This study was the first step towards enhancing our understanding of the relation between eye fatigue and ambient light. Further experimental investigations are required to determine exactly how ambient light affects eye fatigue. We recommend that further research should be done with real radiologists under the same conditions and using same methods, and a performance test may be added in order to investigate the relation between the diagnostic performance and eye fatigue under different ambient lighting settings.

The evidence from this study indicates that there is a relation between eye fatigue and the amount of ambient light. Although, we have obtained satisfactory quantitative and subjective results proving that the eye fatigue was decreased with increasing ambient light between 0 and 50 lux and between 0 and 500 lux; there was no statistically significant difference between 50 and 500 lux.

APPENDIX A. SUBJECTIVE TEST QUESTIONNAIRE

Name: Date:

1) Age _____
2) Sex _____
3) Do you wear any type of corrective lenses? Yes / No
   If yes; Contact Lens / Glasses for _________
4) Do you use any sort of medication which may be effect on the vision? Yes / No
   If yes; what kind of medication do you use? _____________
5) When was your last eye examination? ______
6) How many hours did you sleep last night? _____
7) How many hours do you sleep in average? _____
8) How many hours do you working with the computer on a daily basis? _____
9) Do you working in an environment that illuminated with natural light or do you working in a closed environment like underground offices? _____
10) Do you working in a well-lit environment? Yes / No
11) On a daily basis, how often do you experience the following symptoms after long computer related work? (1-never, 5-always)
    a. Itching, burning or irritated eyes _____
    b. Pain around the eyes _____
    c. Double vision _____
    d. Lack of focusing _____
    e. Headache _____
    f. Color changes _____
    g. Neck soreness _____
12) Please give the answer for the following questions before and after experiment.

	0 Lux		50 Lux		500 Lux	
	Before	After	Before	After	Before	After
Itchy eyes						
Burning eyes						
Irritated eyes						
Pain around the eyes						
Headache						
Heavy eyes						
Lack of focusing						
Double vision						
Color changes						
Neck soreness						

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