# THE EFFECT OF LED PULSE-WIDTH MODULATION OF LIGHT ON VISUAL PERFORMANCE

by

MARIANNA SADE BENITEZ

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Committee Members:

Jennifer Scheib

Sandra Vásconez

Moncef Krarti

Benitez, Marianna Sade (M.S., Civil, Environmental, and Architectural Engineering)

The Effect of LED Pulse-Width Modulation of Light on Visual Performance

Thesis directed by Assistant Teaching Professor Jennifer Scheib

Temporal light modulation (TLM), commonly referred to as "flicker" can create visual discomfort, worsened reading time and accuracy, erratic eye movements, and headaches, among others. In most new construction projects, LED luminaires are being specified in conjunction with a pulse-width modulation (PWM) dimming system. While PWM systems have controllability and energy efficiency advantages over constant current dimming systems, they intentionally introduce TLM into the space due to the varying duty cycle of the LED waveform. To evaluate the impact of TLM likely present in workspaces with LED dimming, we measured reading time and the number of reading mistakes made during a reading task when participants were exposed to LED luminaires with different levels of duty cycle that mimic those in a traditional office setting. Interestingly, there was not sufficient statistical evidence to infer a relationship exists between the duty cycle of an LED light source and the reading time and accuracy of the participants. These findings contribute to the inconsistent results on the effects of TLM in the architectural lighting literature, likely due to the many combinations of environmental variables possible for evaluating human performance under TLM. This suggests that the development of metrics, predictive equations, and TLM standards is necessary for refining experimental research in the area and ultimately understanding the effects of pulse-width modulation on human visual performance.

*Keywords: temporal light modulation, pulse-width modulation, visual performance, duty cycle*

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# CHAPTER I

## INTRODUCTION

The purpose of this study was to determine to what extent the perceptions of temporal light modulation (TLM) from a light-emitting diode (LED) light source and power supply combination impact the viewer's visual performance. The research question is: What is the effect of LED pulse-width modulation (PWM) on human visual performance? The study used an experiment to understand the reading performance of subjects while under different lighting conditions. These factors were evaluated through a repeated measures human factors experiment comparing the participants' reading performance, measured by reading speed and accuracy. The primary hypothesis is that LED PWM with a lower duty cycle will produce worse reading time and accuracy.

### BACKGROUND

In working environments worldwide, LED sources are used and will be used due to the lighting technology's energy efficiency and durability benefits over legacy light sources. However, the quality of light from LED systems is understudied. LEDs operate from a power source which can create temporal fluctuations in light output, also known as temporal light modulation (TLM). TLM varies across four parameters; frequency of the cycle, depth of variation in light output, shape of the waveform, and duty cycle applied to rectangular waves. Duty cycle is a relevant parameter to architectural lighting as most power sources generate rectangular waves. Veitch et al. (2024) describe duty cycle as, "The proportion of the cycle for which there is non-zero light output...expressed as a ratio or a % of the cycle time" (2024, 67). For example, in traditional building applications, TLM is introduced when pulse-width modulation (PWM) is used to dim the fixtures. PWM operates at

100% modulation and turns current on and off rapidly with a varying duty cycle to reduce the average current and light output of the LED (Miller et al. 2022, 55).

Due to findings from the Talbot-Plateau Law, the frequency of the cycling in light output of most commercial lighting products is high enough (greater than 50 to 60 Hz) that observers are not conscious of the change and only see the average light output of the source. The frequency above which the human visual system sees only the average lighting output and not the cycling is referred to as the critical fusion frequency (CFF). However, it has been shown that non-visible light effects can occur at a range of light output frequencies (Veitch et al. 2024; Bullough et al. 2013; Tengelin et al. 2017; Laycox et al. 2024). Additionally, some cycling does cause visual perception effects.

There are three forms of human visual perception effects of TLM which are called temporal light artefacts (Martinsons et al. 2024). Flicker is the term used for a static observer in a static lighted environment (CIE 2020), stroboscopic effect applies to a static observer in a non-static lighted environment, and phantom array describes the effect of a non-static observer in a static lighted environment (CIE 2022). At high (> 500 Hz) and low (< 50 Hz) light cycling frequencies, the TLM has little impact on the human visual system (Veitch et al. 2024). However, at the critical fusion frequency (CFF), the light modulation has an impact on human performance and eye movements (Veitch et al. 2024) indicating the need to observe a complex task for subconscious changes in performance. This study will measure performance disruptions and observe phantom array interactions by participants while the observer is non-static (able to move head and eyes), performing a reading task; and the environment, including the lighting condition, will be static.

## PURPOSE OF THE STUDY

The lack of current literature observing the effects of PWM control of LEDs on human visual task performance has motivated this study. To quantify the effect of TLM on humans, previous studies have observed the number of eye movements, rating of visual discomfort, pupil size, and reading time and accuracy, with the independent variable being the frequency of the light modulation of the LED or fluorescent source. The present study seeks to examine the effect of the PWM of an LED source on reading performance, quantified by reading time and accuracy.

Additionally, this study will use independent variables related to PWM such as duty cycle to ground the work in real architectural lighting product behavior. In real products, when the frequency is a constant value that is at or above the CFF, then a change in the duty cycle creates a noticeable dimming effect. *Equation 1* displays the linear relationship between duty cycle (D), pulse-width (PW), and frequency (f) and how the duty cycle of temporal light modulation can change with a constant frequency (Cox 2001, 515).

Equation 1: Duty Cycle $D = PW * f * 100\%$

The measurements will be taken under photopic illuminance levels in an office setting. The office setting seeks to simulate one instance where the dependent variables can be correlated to human performance applying to all who use general architectural lighting. Due to previous knowledge that TLM values with a larger modulation are preferred less and are more noticeable by participants (Bullough et al. 2013; Olsen et al. 2014), we hypothesize that LED PWM with a lower duty cycle will produce worse reading time and accuracy.

# CHAPTER II

# REVIEW OF THE LITERATURE

Many past research studies have tested the effect of temporal light modulation on human visual task performance. The following sections summarize project scopes, variables, and equipment used. This research survey reveals a gap in the research topic in regards to which variable of TLM is manipulated and the metrics that are used to predict and understand total perceived modulation. The findings guided the design and physical construction of this experimental setup.

## INDEPENDENT AND DEPENDENT VARIABLES

There exists a gap in TLM variable manipulation because many past studies have observed the effects of frequency and modulation depth as the independent variable (Appendix A), though these are only two of the factors that can influence TLM. For example, in the 2024 Veitch et al. study, the levels of the independent variable were zero TLM, 100 Hz, and 500 Hz. They found that Stroop Performance, which is a positve cognitive interference test in which participants named the color of a word when the word and the ink color are mismatched (incongruent) or matched (congruent), were increased at 100 Hz. Similarly, the dipole strength (brain activity measure) were also increased at 100 Hz which they concluded as the critical fusion frequency (CFF). Aside from reading time, Stroop Test time and accuracy, Electroencephalogram (EEG) data, and a State-Train Anxiety Inventory (STAI) survey, Veitch et al. also collected eye-tracking data. The visual performance was quantified by the number of eye movements, eye blinks, eye fixation, saccade amplitude, and pupil size. They found that pupil size was larger at 100 Hz and 500 Hz which shows that the visual system is subconsciously affected at various TLM values.

Similarly, in 2017, Tengelin et al. observed that when the frequency varied for an integrated ceiling and desk light fixture, a frequency of 100 Hz and 357 Hz, respectively, were perceived as the most disturbing for participants. Participants were asked to assess the presence of stroboscopic effect, as either not noticed, noticed but not disturbing, and disturbing. The presence of stroboscopic effect was described to participants as either a discrete or continuous appearance of an object.

Another study performed in 2024 by Laycox et al. showed that reading speed was slowest at 60 Hz in comparison to 120 Hz and 60 kHz. They also found that when the frequency varied from zero TLM, 60 Hz, and 600 Hz, some participants read the fastest when no TLM was present. However, others participants, characterized as "High-Pattern Glare" read the slowest when the frequency varied. The High-Pattern Glare participants were determined if they reported the presence of more than two illusions when observing a grating pattern on a sheet of paper. Some of the illusions could be from observing different colors, bending or blurring lines, shimmering, flickering, fading, or shadowing shapes (Laycox et al. 2024, 515). The reading task designed by Laycox et al. measured the reading speed and accuracy of participants for high and low autocorrelation pieces of text. High autocorrelation can be seen as a striped appearance due to similar letter heights along the words of a sentence. Laycox et al. concluded that High-Pattern Glare participants had exacerbated, slower reading speed, results when presented with high autocorrelation text and at a frequency of 60 Hz.

Another variable of TLM that has been manipulated in past research work is the modulation depth of an LED source's light output. Modulation depth explains the relationship between the LED output maximum and minimum luminance values (of a source or display) as outlined in Equation 2 (Veitch et al. 2024, 67; Jaen 2011, 461).

Equation 2: Modulation Depth

$$\text{Modulation depth (\%)} = 100 * \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})}$$

In 2014, Olsen et al. tested 0%, 29%, and 100% modulation depth at 100 Hz frequency and measured participants' impressions of the different lighting scenes. The results show that all participants noticed flicker when the modulation depth was 100% and that the LED chip colors were seen as separating. Some participants also reported feelings of discomfort and overwhelm at 100% modulation depth (Olsen et al. 2014, 1106).

Moreover, in the 2013 Bullough et al. study, participants were exposed to various frequencies and modulation depths: 100 Hz and 100% modulation depth, 100 Hz and 25% modulation, and 1000 Hz and 100% modulation. The dependent variables were time and accuracy in a numerical verification task, rating their visual comfort, and indicating their preference for the lighting conditions. This study showed a larger quantity of errors and was less preferred at 100 Hz and 100% modulation depth. This supports the use of the percent detection and predicted acceptability rating equations because this combination of variables contained values of 96% predicted detection and -0.6 predicted acceptability value (Bullough et al. 2013, 48). The frequent manipulation of frequency (Appendix A) has influenced the present study to manipulate the duty cycle to broaden this area of TLM research and also ground the work in real architectural lighted settings.

## MATERIALS AND METHODS

Many of the studies were conducted in a test office space which simulates one of the instances in which LED architectural lighting is used most frequently (Tengelin et al. 2017; Olsen et al. 2014; Laycox et al. 2024; Bullough et al. 2013). This is significant because the use of an experimentally controlled environment prevents daylight, material reflectances, and outside lighting sources from impacting the space and participants.

In the office setting, many tasks involved a reading test where reading time and accuracy were measured (Veitch et al. 2024; Bullough et al. 2013; Laycox et al. 2024). By performing a reading task, the grating of letters and numbers on a sheet of paper can create illusions when TLM is present which would allow the study to determine if the presence of TLM impacts the participant's reading performance.

Similar to the Tengelin et al. study, Laycox et al. found that participants scored worse when the mental workload was smaller (Tengelin et al. 2017, 8; Laycox et al. 2024, 523). The level of mental workload was measured by the the text autocorrelation as stated "The words were selected as having a high or low first peak in the horizontal autocorrelation. Examples of words with high first peak were 'new,' 'man,' and 'him.' Examples of words with low first peak were 'day,' 'job,' and "eye'" (Laycox et al. 2024, 514). This has influenced the present study to use a high-autocorrelation reading study which will provide a more difficult reading task requiring precise control of vergence of the participant's eyes to where the subconscious effects of TLM can be measured.

From the literature, it is clear that not only quantitative data can be collected, but also qualitative. Quantitative data has been collected in the forms of reading time, reading accuracy, eye blinks, eye saccades, EEG data, and reaction time. On the other hand, qualitative data such as information from the PANAS scale, ratings of visual discomfort, headaches, stress, fatigue, and ratings of the illuminance in terms of pleasantness, brightness, and light distribution have also been collected to understand the effect of TLM (Kuller et al. 2010; Bullough et al. 2013; Tengelin et al. 2017; Olsen et al. 2014).

Based on the literature available and the understanding of the negative effects of TLM, we hypothesize the following:

**H1:** Task reading times will be the largest when the duty cycle is the smallest at 25%.

**H2:** Task reading mistakes will be the largest when the duty cycle is the smallest at 25%.

# CHAPTER III

# MATERIALS AND METHODS

## MATERIALS

### Lighting Conditions

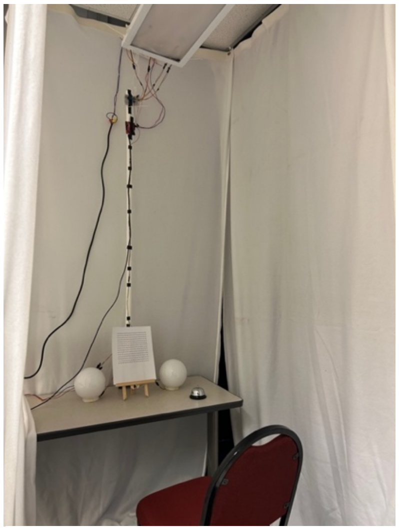

Figure 1: Lighting Condition

The lighting conditions were controlled by three light fixtures; an overhead ambient light source and two desk lamps (*Figure 1*). Both sources contained addressable LED light strips that allowed for direct control of each of the 60 LED chips (Worldsemi n.d.). The ceiling luminaire was 1 ft by 2 ft and contained a diffusing material in front of eight strip lights that were connected in series and parallel to a 5 V power source (*Figure 2*). The two desk lamps had a 4-in diameter, were 6-in tall, and contained one strip light each that were assembled in the same manner as the ceiling luminaire to maintain control and necessary vertical illuminance for the participant (*Figure 2*). The two desk lamps were placed on each side of the reading task for an even distribution. They also utilized a diffuse material to disperse the light within the desk lamp and to prevent glare for the participant.

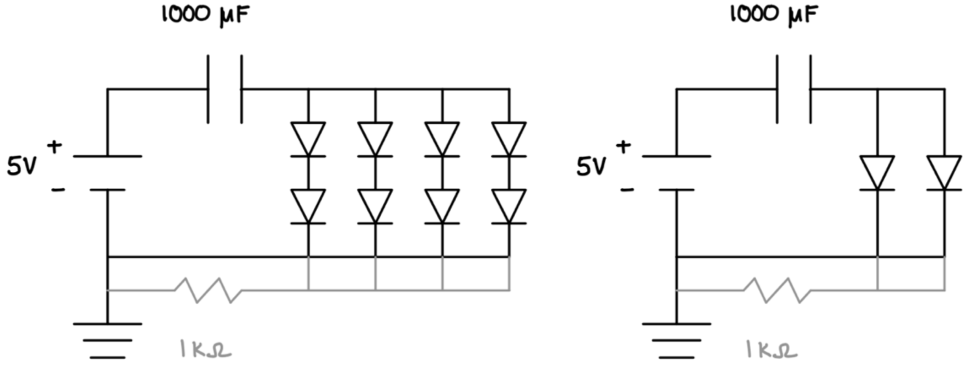

Figure 2: Circuit Diagram of Ceiling Luminaire and Desk Lamps

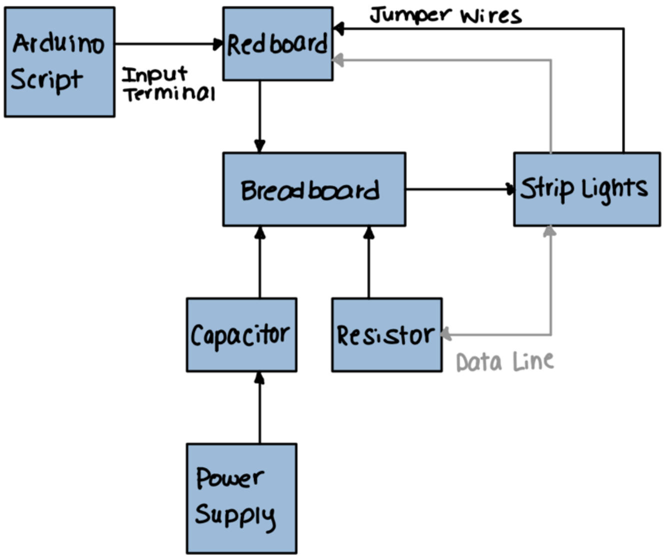

Figure 3: Equipment Assembly Schematic Diagram

The waveform of the strip lights was controlled through an Arduino Redboard (SparkFun n.d.) and breadboard (Kondson n.d.) which was programmed to manipulate the testing variable (*Figure 3*). The voltage from the 5 V power supply was smoothed out with a capacitor (SparkFun n.d.) which ensured a constant voltage displaced the LED strip lights. The data line of the strip lights connected, first to a resistor (SparkFun n.d.) and then, to a PWM pin on the Arduino Redboard which ran the Arduino script and controlled the LED waveform. The manipulation variable contained four duty cycle levels: 25%, 50%, 75%, and 100%. There were four corresponding Arduino scripts used to change the duty cycle and number of chips in operation to maintain a constant horizontal and vertical illuminance of 15 fc and 10 fc, respectively; see Appendix D. For the modulation settings, the LEDs operated with a rectangular wave having 100% modulation depth and 800 kHz frequency (Worldsemi n.d., 3). *Figure 4* displays the differing waveforms when manipulating the duty cycle. While the modulation depth itself was not manipulated because each setting was cycling from full on to full off, the relative lumen output was manipulated to maintain a constant illuminance.

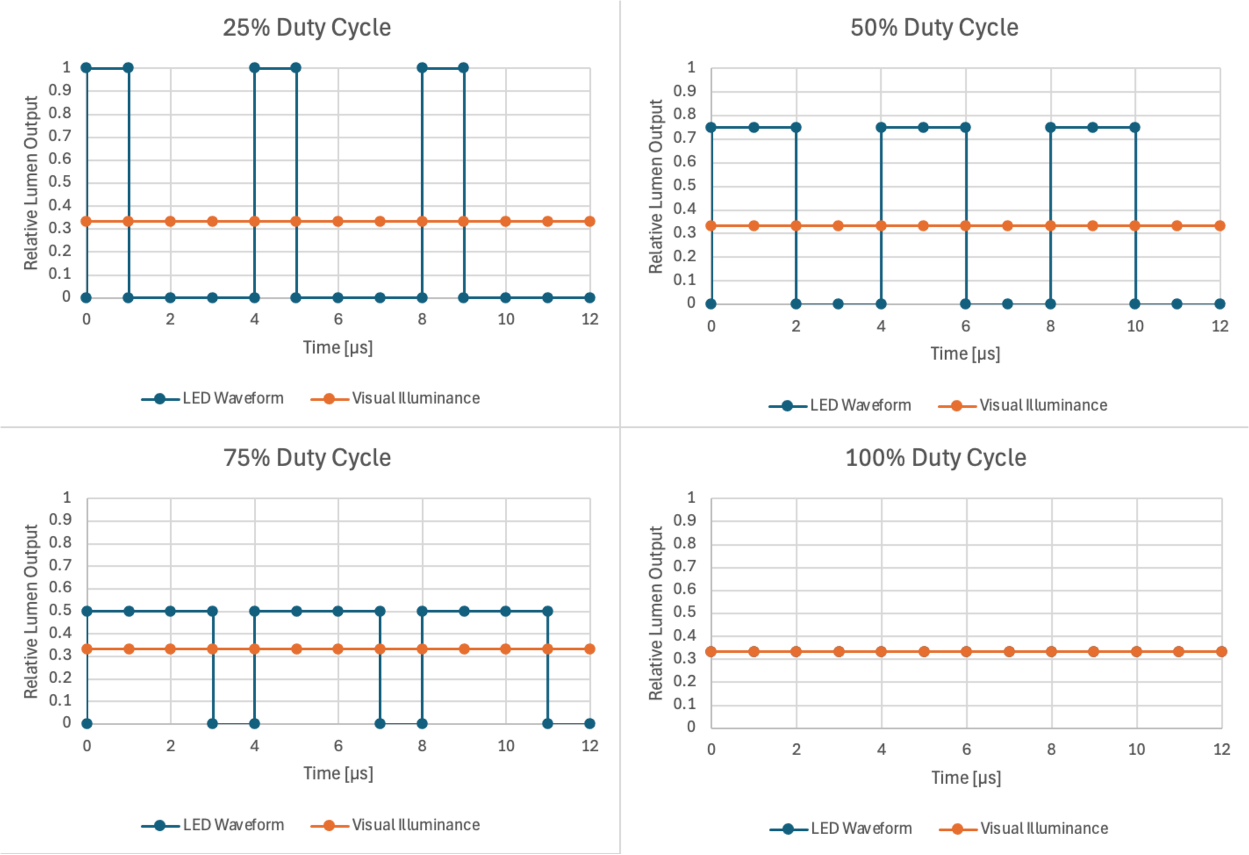

Figure 4: LED Waveforms with Duty Cycle and Relative Lumen Output Manipulations

## Lighting Measurements

Before participants were introduced to the lighting scenes, an oscilloscope (Keysight Technologies 2018) and light meter (Konica Minolta n.d.) were used to ensure control of the electronics and the light levels. The oscilloscope was used to measure and visually present the waveform of the LED light output as it relates to the voltage across the strip lights. Using this tool was essential in understanding and ensuring the waveform changes on the hardware when the duty cycle is manipulated in code.

Second, a light meter was used to ensure the illuminance was maintained at a constant value while the duty cycle, relative lumen output, and number of powered LED chips varied. Per the Illuminating Engineering Society (IES) illuminance recommendations for a reading task, a minimum of 15 footcandles (fc) must be measured at the horizontal task surface in addition to 5 fc at the vertical plane of the reader (IES RP-10-20 2020, 17). Throughout each of the lighting variations, 15 fc horizontally and 10 fc vertically were maintained, respectively. This was done by manipulating the number of chips that were in operation for the 60-chip strip light while the duty cycle changed. *Table 1* displays the pattern of illuminated LED chips for each level of duty cycle.

Table 1: Duty Cycle and LED Chips in Operation for Constant Illuminance

| **Duty Cycle** | **# of LED Chips in Operation** | **Description** |
|---|---|---|
| 25% | 60 | Every 1 LED chip |
| 50% | 45 | Every 3 out of 4 LED chips |
| 75% | 30 | Every 2 LED chips |
| 100% | 20 | Every 3 LED chips |

## Physical Environment

In addition to the three light fixtures, the physical environment was designed to appear as a small private office or cubicle. There was a desk and chair at each end of the 4 ft by 6 ft room, one for the participant and the other for the researcher. The ceiling luminaire was placed directly overhead of the desk and chair for the research at approximately 9 ft above the finished floor. The desk lamps were placed on the desk to each side of the 12-in tall easel which held the reading task (*Figure 5*).

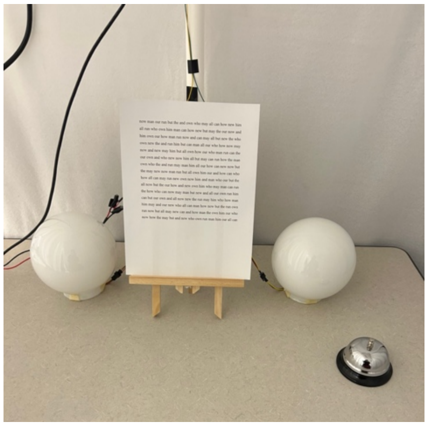

Figure 5: Desk Assembly

Moreover, white curtains were placed along all four walls of the office to maintain constant reflectances along the surfaces (*Figure 6*). White-colored curtains and white ceiling tiles were used to maximize the illuminance in the room as the light reflected off of the curtains and into the space. The window was also covered with a black-out curtain so that the only light sources were the overhead fixture and table lamps.

Figure 6: Office Room Assembly

## METHODS

### Participants

The Institutional Review Board at the University of Colorado Boulder approved the research protocol, including all communications between the researchers and participants. Participants were between 18 and 32 years old and had normal or corrected to normal vision. Forty healthy undergraduate-level participants (19 females, 20 males, one non-binary; mean age 22 years, sd 3.32 years) were recruited through the university's Architectural Engineering and Environmental Design programs. All of these recruitees completed the experiment. All data was retained for analysis.

### Experimental Design and Procedure

The light sources were turned off prior to each testing session to ensure the LED lumen maintenance throughout the duration of the study. Testing sessions began at 8:00 am and lasted through 6:00 pm and each session lasted no more than 30 minutes. Following the consent procedure, participants completed the demographic questionnaire which included questions such as name, age, gender, rating of their reading proficiency on a 5-point Likert scale, and if they wear eye corrective devices; see Appendix B and C. Due to the nature of the reading task, a visual acuity task was then performed using the Graham Field test (Snellen n.d.) to ensure each participant had 20/20 vision.

Then, participants were seated in the office desk with the easel, reading task, and table lamps in front of them. They were exposed to the lighting scene for 30 seconds before they were able to perform the reading task. The four duty cycle settings were randomized and counterbalanced across all participants. The experimental design was a within-subject design and repeated measures, meaning each participant was exposed to the four levels of the manipulation variable. Participants were directed to first strike the desk bell to start the timer, read the passage aloud, and then strike the desk bell to end the timer. Participants were not allowed to use their finger or other object to guide in the reading task and the use of cell phones or activity outside of the office room was prohibited between trials.

Laycox et al. created the reading task which consists of 15 lines of the same 15 autocorrelation words that appeared in a different random order in each line. The text was in Times New Roman font, 18 point size, and 1.5 spacing; see Appendix E. The high autocorrelation words require greater binocular alignment precision and fixation times due to the small text size, small spacing, and similarities in letter shape (Laycox et al. 2024, 516). The complexity of the task was to help ensure that the effects of TLM were observed subconsciously, preventing the participant from becoming aware of the modulation in light output.

## MEASUREMENTS

The reading time was measured by a researcher who was sitting behind the participant in the office space. The researcher started and stopped the stopwatch when the participants pushed the desk bell. The accuracy was also determined by the researcher who took note of when the participant made a reading error. The duty cycle levels were counterbalanced across all participants to account for an increased accuracy with improved familiarity as the participant repeats the reading task. An audio recording was also collected during the experiment for later reference.

# CHAPTER IV

# RESULTS

## READING TIME

The reading time scores were examined using a one-way analysis of variance (ANOVA) with six comparisons: 25% and 50% duty, 25% and 75%, 25% and 100%, 50% and 75%, 50% and 100%, and 75% and 100%. The criterion measure was the continuous measurement of reading time, recorded in seconds. *Table 2* shows the descriptive statistics. At a 95% confidence interval, all levels of the independent variable are normally distributed, have equal variances, and have equal means (p = 0.8545). There is not sufficient statistical evidence to infer that the duty cycle impacts reading time (*Figure 7*). See Appendix F and G for the full results.

Table 2: Reading Time Descriptive Statistics

| **Duty Cycle** | **n** | **mean** | **variance** | **g3. skewness** | **g3test. p** | **g4. kurtosis** | **g4test. p** |
|---|---|---|---|---|---|---|---|
| 25% | 40 | 103 | 204 | 0.05 | 0.89 | -0.58 | 0.41 |
| 50% | 40 | 104 | 245 | 0.31 | 0.38 | -0.79 | 0.17 |
| 75% | 40 | 102 | 188 | 0.42 | 0.25 | -0.33 | 0.74 |
| 100% | 40 | 101 | 218 | 0.75 | 0.05 | 0.53 | 0.37 |

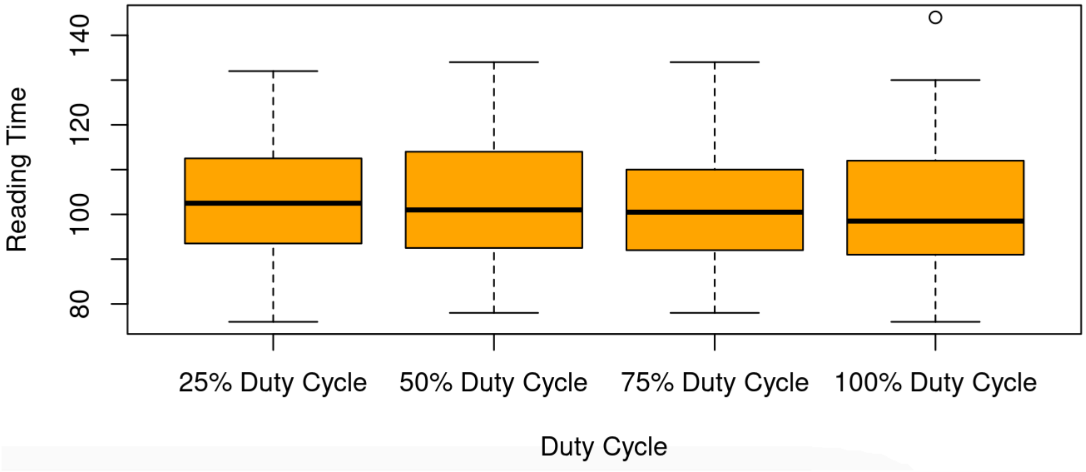

Figure 7: Reading Time by Duty Cycle

READING MISTAKES

The reading accuracy scores were examined using a one-way analysis of variance (ANOVA) with six comparisons: 25% and 50% duty, 25% and 75%, 25% and 100%, 50% and 75%, 50% and 100%, and 75% and 100%. The criterion measure was the counted number of mistakes. *Table 3* shows the descriptive statistics. At a 95% confidence interval, all levels of the independent variable are not normally distributed (*Figure 8*), have equal variances, and have equal means (p = 0.9290). There is not sufficient statistical evidence to infer that the duty cycle impacts the number of reading mistakes (*Figure 9*). See Appendix F and G for the full results.

Table 3: Reading Mistakes Descriptive Statistics

| **Duty Cycle** | **n** | **mean** | **variance** | **g3. skewness** | **g3test. p** | **g4. kurtosis** | **g4test. p** |
|---|---|---|---|---|---|---|---|
| 25% | 40 | 6 | 18 | 1.26 | 0.00 | 1.18 | 0.13 |
| 50% | 40 | 6 | 12 | 0.45 | 0.22 | -0.67 | 0.29 |
| 75% | 40 | 6 | 22 | 1.17 | 0.00 | 1.34 | 0.10 |
| 100% | 40 | 6 | 23 | 1.12 | 0.01 | 0.77 | 0.25 |

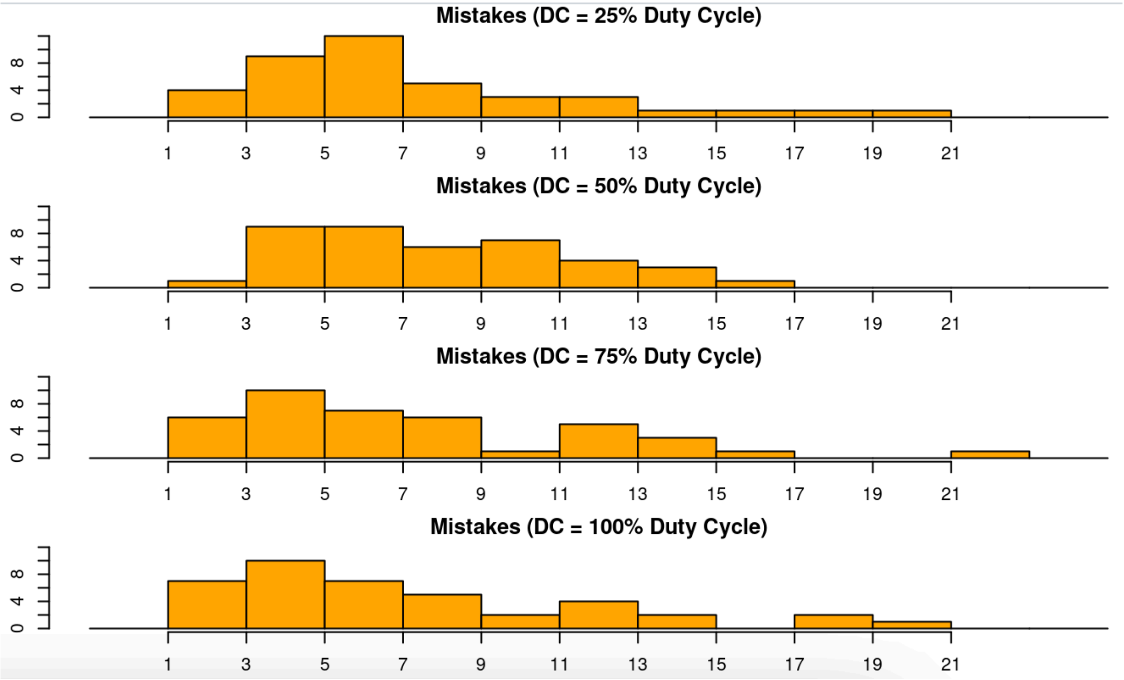

Figure 8: Reading Mistakes Graphical Statistics

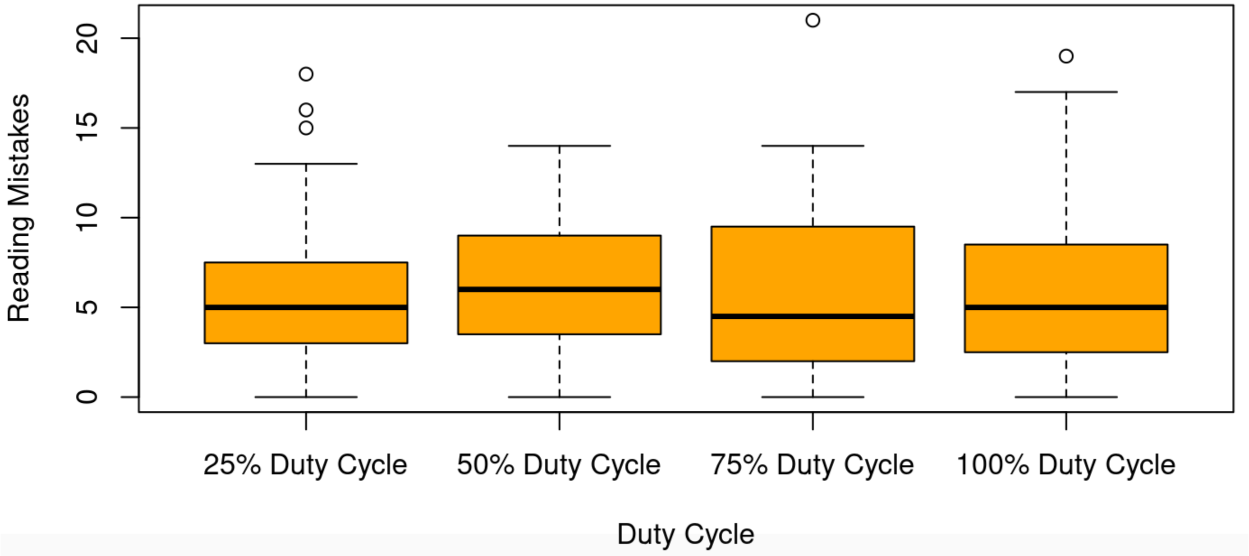

Figure 9: Reading Mistakes by Duty Cycle

# CHAPTER V

# DISCUSSION

## THEORETICAL IMPLICATIONS

### Reading Speed

It was predicted that temporal light modulation at low duty cycles might create longer reading times and slower reading speeds. To the best of our knowledge, there have not been other studies comparing the combination of duty cycle and reading time. With respect to variability in the means of reading time, there was no difference in variability and no difference in dispersion when comparing the four levels of duty cycle; 25%, 50%, 75%, and 100%.

Even though no difference in reading time was detected due to the four levels of duty cycle, with PWM systems used in architectural settings, dimming is offered down to a duty cycle of 1%. Therefore, the question of the effect of duty cycle on reading time remains true but needs to be studied concerning duty cycles lower than 25%.

The observations are consistent with the understanding that humans exhibit wide variations in sensitivity to TLM (Miller et al. 2022, 28; Martinsons et al. 2024; Laycox et al. 2024; Tengelin et al. 2017; Olsen et al. 2014). Because TLM is associated with different sensitivity functions, viewing conditions, and physiological and cognitive mechanisms (Bodington et al. 2015), population norms and remedial measures remain unknown. As shown in past research, sensitivity is impacted by age, headache occurrences, (Brundrett 1974), and visual disturbances when reading (Harle et al. 2006; Laycox et al. 2024), among others. This may provide an explanation as to why there was no trend in the data for reading time when participants were introduced to different levels of duty cycle.

### Reading Accuracy

It was also predicted that temporal light modulation at low duty cycles might create a greater quantity of reading mistakes and a worsened reading accuracy. With respect to variability in the means of reading mistakes, there was no statistical effect when comparing the four levels of duty cycle; 25%, 50%, 75%, and 100%. Although no difference in reading time was detected due to the four levels of duty cycle, it is important to learn more about the effect of duty cycle on productivity and to what extent TLM is acceptable for those in LED-lighted spaces.

This study also reinforces the need for a metric that quantifies the prediction of the phantom array effect (Martinsons et al. 2024) and the need for recommendations and specifications of acceptable TLM quantities for architectural environments (Miller et al. 2022). As stated, "In fact, there are no prediction tools at all for the phantom array effect, which results from a waveform with deep modulation that was rarely seen before LEDs entered the marketplace" (Miller et al. 2022, 5). This shows that when the modulation depth is 100%, as seen in the operation of LED luminaires, there are no metrics that predict human detection, acceptability (Bullough et al. 2013; CIE 2022), or index of flicker (Bodington et al. 2015) as used in previous research work. With the use of a metric relating to the phantom array effect, the design of research studies manipulating duty cycle can clearly quantify and understand the effect duty cycle can have on visual performance.

Moreover, current recommendations and specifications of acceptable TLM limits have been developed for LED outputs as a sine wave function (IEEE 1789 2015) which neglects the existence of duty cycle in rectangular wave functions. Since these standards were developed before the adoption of LED light sources and introduction of PWM dimming, there exists a new demand to standardize acceptable duty cycle limits for environments that may introduce the phantom array effect.

## POTENTIAL LIMITATIONS

### Frequency

The first limitation of the thesis question is due to the constant operation frequency of 800 kHz from the LED strip lights (Worldsemi n.d., 3). Since each chip of the LED strip light needed to be directly addressable, the use of prototyping equipent was required. Commercial luminaire products were deemed unacceptable for the desired function of the LED technology and were therefore excluded. As a result, the building operational frequency of 50 to 60 Hz could not be incorporated into this study.

This 800 kHz frequency is significant because it is much higher than the upper end of frequency values used in precedent studies (*Figure 10*). This may have impacted the study by negatively influencing the results and limiting the predictability of TLM effects. More specifically, percent detection and predicted acceptability ratings have a maximum value of 10 kHz (Bullough et al. 2014, 189) whereas perceived modulation has a maximum frequency of 90 Hz (Miller et al. 2022, 17). This shows that many TLM metrics have established an ideal frequency range which has been deemed unapplicable to the current study due to the LED technology used. The unwanted effects of the high

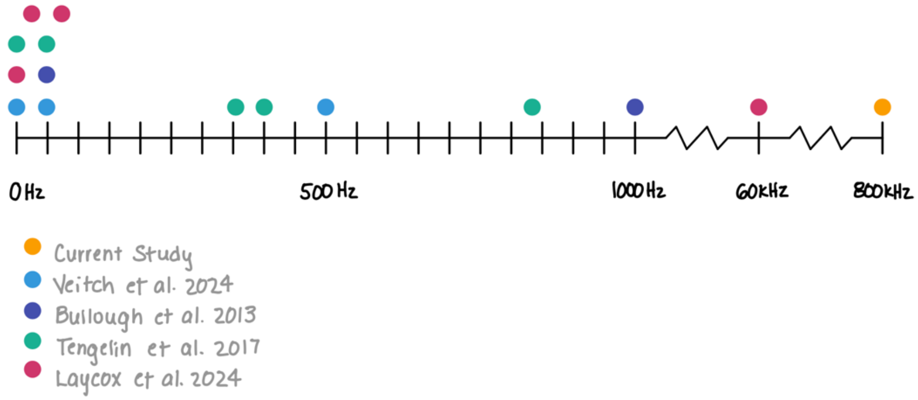

Figure 10: Frequency of Precedent and Current TLM Studies

operation frequency may have caused the effect of duty cycle manipulation to not manifest in the data.

To directly compare the research study to architectural settings, then the frequency should also match those of real luminaire products. Due to building electrical systems operating around 50 to 60 Hz, the 800 kHz light strips used in this study should be replaced or manipulated to decrease the operation frequency. Matching the frequency of the study to those of commercial products would allow the study to accurately correlate results to architectural environments.

In the future, a commercial luminaire or waveform generator could be used to allow direct control of the frequency while also allowing customization of the duty cycle. If a waveform generator is used to control the LED output, then the frequency can be established and held constant throughout the study. By setting a frequency within the ranges of TLM metrics, the effects can be predicted and guide the study design before data collection.

### Exposure Time

The second potential limitation of the study is the length of time participants were exposed to the lighting scenes. To minimize time for participants in the lab, for each level of the independent variable, participants were exposed to the lighting scene for 30 s before performing the reading task. Following the initial exposure time, participants were only under the lighting scene for the remaining time it took to complete the reading task. At a minimum and maximum, participants were exposed to each lighting scene for a total time between 106 s and 174 s, respectively.

With such limited time being under the lighting scenes, the true effects of the duty cycle on the reading time and number of reading mistakes may not have been captured during data collection. In the future, this can be developed by lengthening the amount of exposure time before participants begin the reading task and potentially including a task that requires a longer completion duration.

## Luminous Environment

Due to the necessary ability to control each LED chip in the strip light using prototyping hardware, the use of commercial products was not possible for this study. As a result, the luminous environment from the strip lights may have introduced some limitations in the uniformity, frequency of TLM, and illuminance at the task or eye level of participants.

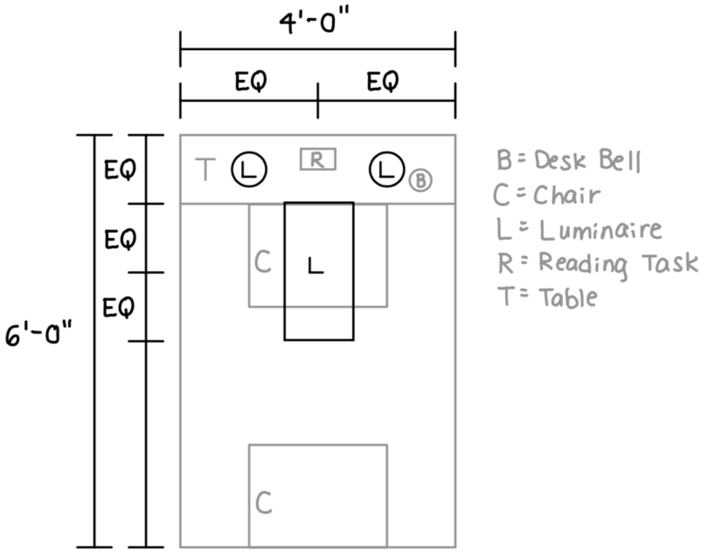

Figure 11: Office Room Floor Plan

While the participant was located directly beneath the ceiling luminaire (*Figure 11*), there was a non-uniform distribution of light throughout the office space. Similarly, the desk lamps were located at a lower height than the reading task easel and may not have been in the direct line of sight of the participant. The height of the desk lamps is significant because the light from these sources was intended to reach the eye of the participant, referred to as luminance. If the height was aligned with the reading task, then the question of the effect of PWM may have been fully captured during data collection.

Although the office space meets the requirements from the IES standards of 15 fc on the task surface and 10 fc of vertical illumination, many office spaces are achieving a larger average illuminance than is required. With a larger average illuminance in the space, the effects of the changing duty cycle on reading time and the number of reading mistakes may be more apparent.

In the future, the luminous environment can be improved by using a larger quantity of LED strip lights, increasing the number of luminaires in the space, and/or increasing the height of the desk lamps. By using a larger quantity of LED strip lights, the ceiling and table lamps can increase the lumen output which will also increase the illuminance in the space. Moreover, if more luminaires are used at the correct height in the space, the light uniformity can be improved to ensure light fills the entire space and reaches the eye, not solely on the working space of the participant.

## Correlated Color Temperature

Each chip in the LED strip light is composed of three colored diodes, red (R), green (G), and blue (B) (*Figure 12*). When each diode emits light at an equal proportion, white light is produced. However, due to the nature of the LED strip lights, each diode operates at a different voltage with the R diode accepting 1.8 to 2.2 V, the G diode accepting 3.0 to 3.2 V, and the B diode accepting 3.2 to 3.4 V (Worldsemi n.d., 4). As a result, when the duty cycle was manipulated, this changed the voltage that displaced the three diodes and therefore caused different color output among the four trials of the experiment. By using an illuminance spectrophotometer (Konica Minolta 2011), the CCT measurements could be collected at each of the four duty cycle levels. *Table 4* showcases the wide range of CCT values as the changing voltages displaced the R,G, and B diodes.

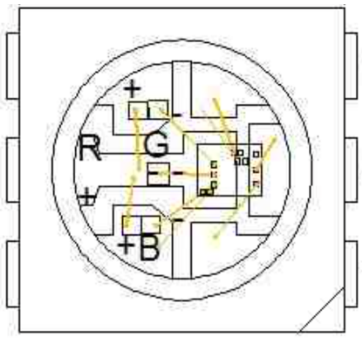

Figure 12: LED Chip (Worldsemi n.d., 2)

Table 4: Correlated Color Temperature of Duty Cycle Levels

| **Duty Cycle** | **Correlated Color Temperature (CCT)** |
|---|---|
| 25% | 2677K |
| 50% | 4551K |
| 75% | 4729K |
| 100% | 7436K |

While correlated color temperature (CCT) was not part of the original research question, there arises a sub-question that highlights the potential effect of the changing CCT on visual performance. As seen in past research, there are quicker reaction times when the CCT increases and at greater short wavelength content because the S-cones have increased excitation levels and are maximized at 420 nm and 500 nm (Vicente et al. 2023; Goswami et al. 2022; Dong et al. 2017). In the future, the changes in correlated color temperature could be designed into the experiment by directly controlling and normalizing the output of each R, G, and B diode.

### Language

The third potential limitation of the study is the relationship between the language of the reading task and the language that each participant speaks. Since recruitment was conducted at the University of Colorado Boulder, there was a large quantity of participants who were international students. Due to this, English was not the first and only language that participants spoke. This might have impacted the results by causing longer reading times and a greater quantity of mistakes, due to those who speak other languages and learned English second or later on in life, rather than from the effect of PWM.

In an effort to address this concern, there was a question in the demographic questionnaire that asked participants to rate their English reading proficiency on a 5-point Likert scale with 5 being excellent and 1 being poor. However, the problem with this question is that even participants who are international students and learned English as a second or third language can still have excellent reading proficiency. Also, participants who are from the U.S. and learned English first, and only speak English, could still rate their reading proficiency poorly.

In the future, the effect of language can be accounted for in the study if instead, a question asks what order they learned English, rather than their rating of their English reading proficiency. By doing this, participants who learned a language other than English first in life could be distinguished in the statistical analyses to understand if there is an additional impact on reading time and reading accuracy.

## FURTHER RESEARCH

### Eye Tracking

Further development of the current research study can also measure the number of eye blinks and saccade amplitude to better understand the effects of TLM on the human visual system as done in the Veitch et al. (2024) study. For a more robust examination of the effect of LED pulse-width modulation of light on visual performance, eye tracking should be included. Eye disruptions due to PWM can be quantified by the number of eye blinks and saccade amplitude while the participant is performing the reading task. The use of eye tracking equipment would be similar to the Veitch et al. (2024) and Jaen et al. (2011) studies in which they collected similar eye movement data to better understand visual performance when participants are exposed to TLM. Not only can eye blinks and saccade amplitude be collected, but also the number of fixations and pupil size.

Equipment such as EyeLink 1000 Plus (SR Research 2017) or Tobii Pro Glasses 3 (Tobii AB 2024) are often used in experimental research applications because of their physical flexibility and wide range of eye saccade quantitative data collection. Due to the nature of eye movements, the equipment would be required to operate at a frequency of 100 Hz, or better, for saccade research. At this operating frequency, the gaze path of the participant and accuracy to 0.5 degrees can be collected. With a 0.5 degree gaze path accuracy, the typical length of the task from the participant would allow the researcher to understand how the participant's eyes move across each word and if they go back to read missed words.

These two eye-tracking tools could also be used seamlessly with the current experimental assembly as the EyeLink 1000 Plus equipment rests on the table and is a camera that is angled towards the eyes. This would allow the arms to move freely to press the desk bell. On the other hand, the Tobii Pro Glasses are instead worn by the participant but also allow the arms to move freely which shows that the same task and set-up could be used even when introducing more equipment and data collection.

Relating back to the office setting, the flexibility of the equipment would maintain a stress-free environment, relative to a more physically constraining eye-tracking setup. This is important to the data collection because the conclusions could be related to an office setting, rather than being applicable only to the experimental set-up.

### Custom Computer Monitor

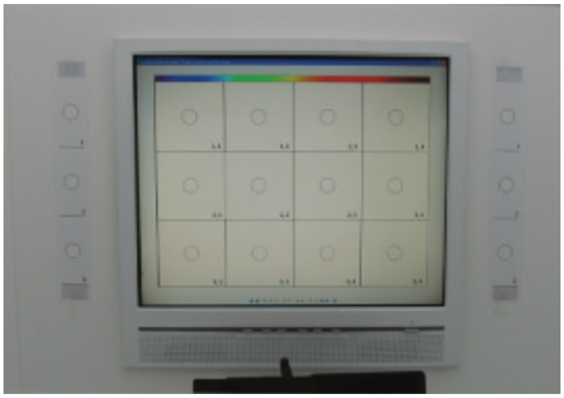

Figure 13: Custom Computer Monitor (Veitch et al. 2024, 90)

Similar to the Veitch et al. (2024) study, a more developed analysis could also include the use of a custom computer monitor which would broaden the number of tasks to be completed (*Figure 13*). The monitor also increases the potential of an integrated data collection system where the dependent variable of reading time, among others, could be tracked simultaneously. A computer monitor set-up would not only increase the number of tasks, but it would also reinforce the imitation of an office setting as paper tasks are not as common in the office anymore.

The challenge with using a computer monitor is the fact that the LCD screen contains its own luminaires that operate at unknown TLM values. Therefore, the original fluorescent backlight would need to be removed and replaced with an LED light source that would match the ambient luminaires. By doing this, both the monitor and overhead luminaires could be connected in parallel to the power source and operate at equivalent duty cycles.

Larger computer monitors are backlit where the fluorescent lights emit light in 360 degrees and the combination of the LCD screen optics uniformly distribute the light across the screen. However, if the fluorescent sources are replaced with LEDs, then the light is emitted in a Lambertian form, or directionally, from the chip base and might create hotspots on the LCD screen. Therefore, before introducing participants, the uniformity of the screen luminance must also be measured and maximized. *Equation 3* outlines how Veitch et al. calculated the non-uniformity of 12 measurement targets to ensure the custom monitor aligned with the non-uniformity of the monitor before the fluorescent lights were replaced (Veitch et al.

2024, 91). Not only does the light distribution on the computer screen need to be consistent, but also the average luminance to ensure appropriate and consistent light levels.

Equation 3: Non-Uniformity $$\text{Non-Uniformity (\%)} = 100 * \left[1 - \frac{L_{min}}{L_{max}}\right]$$

Another challenge with using a computer monitor is the refresh rate that operates at a set frequency, one of the variables of TLM. However, the visibility of the refresh rate could be determined empirically, as outlined by Veitch et al. by using an optical chopper to examine the differences in appearance of a chopper wheel with and without the monitor (Veitch et al. 2024, 91).

### Conscious Awareness

Another area of potential future work lies in the conscious awareness of TLM changes due to the duty cycle. While this question was not accounted for during the data collection period, the question of the effect of duty cycle on conscious awareness of TLM remains true. While the high-autocorrelation task developed by Laycox et al. was designed to require greater precision of binocular alignment and longer fixation times (2024, 513), it was unclear in the present study if participants were aware of the TLM throughout the study.

The development of a participant's conscious awareness of TLM can be captured in the future through a post-exposure questionnaire or journal entries done before, during, and after exposure. Not only can the questionnaire or journal entry efforts collect data on the immediate awareness of TLM, but this can also develop the understanding of the long-term effects of TLM exposure. These effects can often manifest in the form of eyestrain, headache, and fatigue (Martinsons et al. 2024, 66) but this question is not often addressed or made known when participants leave the experiment. The conscious awareness and long-term effects of a changing duty cycle are significant in understanding if PWM dimming systems create present awareness and future health challenges.

Research considering the conscious awareness of TLM should not only include the average (or normal) participant but also sensitive observers who experience headaches and migraines. Since most metrics are developed from research conducted on the average participant (Miller et al. 2022), there lies a gap in the research and conclusions drawn about how reliable TLM detection is quantified. By including these sensitive participants, a more complete analysis and development of TLM metrics can be done to address the most severe effects of TLM.

# CHAPTER VI

# CONCLUSION

Understanding the effects of TLM on observers in architectural environments is of more than theoretical interest because the intentional presence of TLM due to PWM systems poses significant health risks to individuals (IEEE 2015; Martinsons et al. 2024). Several research studies have examined the effect of TLM due to LED light sources with varying frequencies and modulation depth properties, (Veitch et al. 2024; Bullough et al. 2013; Tengelin et al. 2017; Olsen et al. 2014; Laycox et al. 2024) but TLM due to varying duty cycle values remains an area of interest.

This investigation showed that TLM conditions due to varying duty cycles may not have a direct impact on reading time and reading accuracy. While previous research has shown that a frequency range of zero Hz to 1,000 Hz does effect reading time and accuracy (Veitch et al. 2024; Tengelin et al. 2017; Bullough et al. 2013; Laycox et al. 2024), the frequency of 800 kHz is outside of what has been tested before. Since the study tested at an extreme frequency of 800 kHz and did not test at minimum duty cycle levels, the entire range of TLM was not tested and explored. Therefore, at the frequency of 800 kHz and duty cycle levels of 25%, 50%, 75%, and 100%, the effects of TLM on reading time and accuracy did not manifest.

However, the development of evidence-based metrics and standards that set acceptable limits and guidelines on the use of PWM system characteristics is necessary for the productivity and individual responses of all observers. Moreover, a baseline metric describing the characteristics of the phantom array effect could be an advantage used in future research designs.

Future work could integrate eye-tracking equipment and a custom computer monitor for a more robust design. The investigation of varying duty cycle with 50 to

60 Hz of frequency, commercial rather than prototyping equipment, increased exposure time, consistent CCT, participant's first-learned language, and conscious awareness of TLM may also play a role in understanding the effects of duty cycle on visual performance.

In conclusion, this experiment may stand as the first of its kind, combining a high auto-correlation reading task and varying duty cycles to study the effects of TLM at duty cycles that can occur with present-day LED PWM lighting systems. While no trends in the data were made apparent, much more remains to be learned about how TLM impacts the visual performance of people experiencing and working in architecturally lighted environments.

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# APPENDIX

## A. LITERATURE REVIEW INDEPENDENT AND DEPENDENT VARIABLES

| Study Name and Author | Independent Variables | Independent Variables Levels | Dependent Variables |
|---|---|---|---|
| Effects of TLM on Cognitive Performance, Eye Movement, and Brain Function (Veitch et al. 2024) | Frequency | 0 TLM<br>100 Hz<br>500 Hz | Reading time<br>Stroop test - time and accuracy<br>Eye tracking - # of eye movements, eye blinks, fixation, pupil size<br>EEG<br>STAI Survey |
| The Impact of Flicker from Fluorescent Lighting on Well-Being, Performance, and Physiological Arousal (Kuller et al. 2010) | Ballast type | Core-coil magnetic<br>High-frequency electronic | Affective state - activation, orientation, evaluation, control<br>PANAS scale<br>Subjective ratings - visual discomfort, headache, feelings of stress, fatigue<br>Rating illumination - pleasantness, brightness, flicker, lighting distribution<br>Reading test - time and accuracy |
| Visual Task Performance and Perception of Lighting Quality Under Flickering Illumination (Bullough et al. 2013) | Frequency and modulation | 100 Hz, 100% mod (base)<br>100 Hz, 25% mod<br>1000 Hz, 100% mod | Numerical verification - time and accuracy<br>Visual comfort rating<br>Indicate which condition most/least preferred<br>And reduce illuminance until visual quality of base condition |
| Effects of Non-Visual Optical Flicker in an Office with Two Different Light Sources (Tengelin et al. 2017) | Frequency | Ceiling, Desk<br>0 TLM, No TLM<br>400 Hz, 357 Hz<br>357 Hz, 100 Hz<br>100 Hz, 357 Hz<br>100 Hz, 100 Hz<br>833 Hz, 357 Hz | Notice of stroboscopic effects and if it was disturbing<br>Attention test<br>Reaction time test |

| | | | |
|---|---|---|---|
| Human Factors Study on Light Modulation in Indirect Office Lighting (Olsen et al. 2014) | Modulation | 0% (DC control)<br>29%<br>100% | Impressions from Likert scale<br>Word selection/clouds |
| Flicker and Reading Speed: Effects on Individual Visual Sensitivity (Laycox 2024) | Text type<br><br>Frequency | High, low autocorrelation<br>No TLM (experiment 2), 60 Hz, 120 Hz, 60 kHz | Pattern glare test<br>Reading - speed and accuracy<br>Headache questionnaire |

## B. CONSENT FORM

Title of research study: The Effect of LED Pulse-Width Modulation of Light on Visual Performance

IRB Protocol Number: 24-0778

Investigator: Jennifer Scheib, Marianna Benitez

### Purpose of the Study

The purpose of the research is to investigate if a relationship exists between visual performance and the PWM dimming functions used in LED light sources. We expect that you will be in this research study for 30 minutes total and that an approximate of 40 people will participate in the study.

If you have vision related medical history, migraines, or risk of seizures you are not able to participate in the study. Whether or not you take part in this research is your choice. You may experience eye fatigue but you can leave the research at any time, and it will not be held against you.

### Explanation of Procedures

Your study will take place at the Lighting Lab in the Engineering Center Building. During your visit, you will first perform a visual acuity test to confirm you achieve 20/20 vision. Then, you will sit at a desk in a private room and perform a reading task out loud, this will be completed four times. Your visit will be audio recorded. Study staff will escort you into the room and set up the reading task and will be located in the room while you complete the tasks. The tasks will take approximately 30 minutes total. When you have completed all trials of the study, you may leave the room.

You will not be paid to be in this study. If you are a CU Boulder student within an Architectural Engineering course, you will be offered extra credit if you participate in the study, if this has been communicated by your instructor during the announcements of this study.

Confidentiality

Information obtained about you for this study will be kept confidential. The information from this research may be published for scientific purposes; however, your identity will not be given out. Audio recordings will be transcribed; any identifying information will be removed during transcription. The audio files will be deleted after transcription is completed.

Questions

If you have questions about the research, you can contact the Co-Investigator at marianna.benitez@colorado.edu

If you have concerns or complaints about the research, you can contact the CU Boulder IRB at (303) 735-3702 or irbadmin@colorado.edu

Signatures

Your signature documents your permission to take part in this research.

_______________________________________________________________

Signature of subject Date

________________________________

Printed name of subject

_______________________________________________________________

Signature of person obtaining consent Date

________________________________

Printed name of person obtaining consent

## C. DEMOGRAPHIC QUESTIONNAIRE

Title of research study: The Effect of LED Pulse-Width Modulation of Light on Visual Performance

IRB Protocol Number: 24-0778

Investigator: Jennifer Scheib, Marianna Benitez

Demographic Questions

1. What is your first and last name?
    a. ______________________________
2. What is your age?
    a. ______________________________
3. What is your gender?
    a. Male
    b. Female
    c. Non-binary
    d. Other
    e. Prefer not to answer
4. Rate your English reading proficiency on a 5-point scale with 5 being excellent and 1 being poor.
    a. _________
5. Do you wear eye correction devices such as contacts or glasses?
    a. Yes
    b. No

## D. LIGHTING SCENE PROGRAM

25% Duty Cycle

```
#include <FastLED.h>
// How many leds in your strip?
#define NUM_LEDS 120
#define NUM_LEDS2 240
// For led chips like WS2812, which have a data line, ground, and power, you just
// need to define DATA_PIN.
#define DATA_PIN 9
#define DATA_PIN2 10
// Define the array of leds
CRGB leds[NUM_LEDS];
void setup() {
    // ## Clockless types ##
    FastLED.addLeds<NEOPIXEL, DATA_PIN>(leds, NUM_LEDS);  // GRB ordering is assumed
    FastLED.addLeds<NEOPIXEL, DATA_PIN2>(leds, NUM_LEDS2);
}
void showAnalogRGB(const CRGB& rgb)
{
  analogWrite(DATA_PIN,255);
  analogWrite(DATA_PIN2,255);
}
void loop()
{
  for(int i = 0; i < NUM_LEDS; i++)
  {
```

```
    if (i % 1 == 0){ // every led
      leds[i] = CRGB(64,64,64); // 25% output
    } else {
      leds[i] = CRGB(0,0,0);
    }
  }
  FastLED.show();
  }
```

50% Duty Cycle

```
#include <FastLED.h>
// How many leds in your strip?
#define NUM_LEDS 120
#define NUM_LEDS2 240
// For led chips like WS2812, which have a data line, ground, and power, you just
// need to define DATA_PIN.
#define DATA_PIN 9
#define DATA_PIN2 10
// Define the array of leds
CRGB leds[NUM_LEDS];
void setup() {
    // ## Clockless types ##
    FastLED.addLeds<NEOPIXEL, DATA_PIN>(leds, NUM_LEDS);  // GRB
ordering is assumed
    FastLED.addLeds<NEOPIXEL, DATA_PIN2>(leds, NUM_LEDS2);
}
```

```
void showAnalogRGB(const CRGB& rgb)
{
  analogWrite(DATA_PIN,255);
  analogWrite(DATA_PIN2,255);
}
void loop()
{
  for(int i = 0; i < NUM_LEDS; i++)
  {
    if (i % 4/3 == 0){ // every 4/3 leds
      leds[i] = CRGB(128,128,128); // 50% output
    } else {
      leds[i] = CRGB(0,0,0);
    }
  }
  FastLED.show();
  }
```

75% Duty Cycle

```
#include <FastLED.h>
// How many leds in your strip?
#define NUM_LEDS 120
#define NUM_LEDS2 240
// For led chips like WS2812, which have a data line, ground, and power, you just
// need to define DATA_PIN.
#define DATA_PIN 9
#define DATA_PIN2 10
```

```
// Define the array of leds
CRGB leds[NUM_LEDS];
void setup() {
    // ## Clockless types ##
    FastLED.addLeds<NEOPIXEL, DATA_PIN>(leds, NUM_LEDS);  // GRB
ordering is assumed
    FastLED.addLeds<NEOPIXEL, DATA_PIN2>(leds, NUM_LEDS2);
}

void showAnalogRGB(const CRGB& rgb)
{
  analogWrite(DATA_PIN,255);
  analogWrite(DATA_PIN2,255);
}
void loop()
{
  for(int i = 0; i < NUM_LEDS; i++)
  {
    if (i % 2 == 0){ // every 2 leds
      leds[i] = CRGB(192,192,192); // 75% output
    } else {
      leds[i] = CRGB(0,0,0);
    }
  }
  FastLED.show();
  }
```

100% Duty Cycle

```
#include <FastLED.h>
// How many leds in your strip?
#define NUM_LEDS 120
#define NUM_LEDS2 240
// For led chips like WS2812, which have a data line, ground, and power, you just
// need to define DATA_PIN.
#define DATA_PIN 9
#define DATA_PIN2 10
// Define the array of leds
CRGB leds[NUM_LEDS];
void setup() {
    // ## Clockless types ##
    FastLED.addLeds<NEOPIXEL, DATA_PIN>(leds, NUM_LEDS);  // GRB
ordering is assumed
    FastLED.addLeds<NEOPIXEL, DATA_PIN2>(leds, NUM_LEDS2);
}

void showAnalogRGB(const CRGB& rgb)
{
  analogWrite(DATA_PIN,255);
  analogWrite(DATA_PIN2,255);
}
void loop()
{
  for(int i = 0; i < NUM_LEDS; i++)
  {
```

```
  if (i % 3 == 0){ // every 3 leds
    leds[i] = CRGB(255,255,255); // 100% output
  } else {
    leds[i] = CRGB(0,0,0);
  }
}
FastLED.show();
}
```

E. READING TASK

now man our run but the and own who may all can how new him
all run who own him man can how new but may the our now and
him own our how man run now and can may all but new the who
own new the and run him but can man all our who how now may
now and new may him but all own how our who man run can the
our own and who new now him all but may can run how the man
own who the and run may man him all our how can new now but
the may new now man run but all own him our and how can who
how all can may run new own now him and man who our but the
all now but the our how and new own him who may man can run
the how who can now may man but new and all our own run him
can but our own and all now new the run may him who how man
him may and our new who all can man how now but the run own
run now but all may new can and how man the own him our who
now how the may but and new who own run man him our all can

## F. RAW DATA

| **Participant #** | **Age** | **Gender** | **English** | **EyeWear** | **20/20 Vision** | **25 Time** | **25 Mistakes** | **50 Time** | **50 Mistakes** | **75 Time** | **75 Mistakes** | **100 Time** | **100 Mistakes** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 25 | Male | 3 | No | Yes | 80 | 6 | 81 | 4 | 78 | 1 | 76 | 1 |
| **2** | 23 | Female | 5 | No | Yes | 104 | 4 | 91 | 3 | 80 | 2 | 83 | 0 |
| **3** | 22 | Male | 5 | Yes | Yes | 110 | 6 | 104 | 3 | 102 | 5 | 99 | 1 |
| **4** | 21 | Male | 5 | Yes | Yes | 97 | 5 | 98 | 3 | 94 | 6 | 92 | 2 |
| **5** | 20 | Female | 5 | No | Yes | 102 | 3 | 87 | 5 | 88 | 3 | 91 | 6 |
| **6** | 21 | Female | 4 | Yes | Yes | 99 | 4 | 78 | 6 | 84 | 7 | 83 | 5 |
| **7** | 19 | Non-binary | 5 | No | Yes | 98 | 4 | 104 | 3 | 90 | 1 | 93 | 0 |
| **8** | 21 | Female | 5 | Yes | Yes | 98 | 3 | 108 | 7 | 93 | 3 | 93 | 5 |
| **9** | 29 | Male | 5 | No | Yes | 91 | 1 | 119 | 2 | 101 | 1 | 98 | 5 |
| **10** | 22 | Female | 4 | No | Yes | 103 | 1 | 109 | 2 | 103 | 3 | 102 | 1 |
| **11** | 22 | Male | 5 | No | Yes | 87 | 3 | 94 | 5 | 83 | 1 | 95 | 6 |
| **12** | 21 | Female | 5 | Yes | Yes | 97 | 5 | 100 | 10 | 97 | 12 | 95 | 8 |
| **13** | 22 | Female | 5 | No | Yes | 121 | 8 | 120 | 6 | 128 | 5 | 112 | 2 |
| **14** | 22 | Male | 5 | No | Yes | 103 | 6 | 95 | 13 | 107 | 11 | 97 | 11 |
| **15** | 21 | Male | 5 | No | Yes | 117 | 1 | 124 | 7 | 118 | 0 | 112 | 4 |
| **16** | 20 | Male | 5 | Yes | Yes | 94 | 0 | 97 | 0 | 109 | 1 | 91 | 1 |
| **17** | 21 | Male | 5 | No | Yes | 82 | 3 | 84 | 4 | 91 | 3 | 88 | 3 |
| **18** | 21 | Male | 5 | Yes | Yes | 129 | 11 | 129 | 10 | 118 | 4 | 123 | 3 |
| **19** | 22 | Male | 5 | No | Yes | 111 | 7 | 114 | 9 | 103 | 5 | 117 | 11 |
| **20** | 20 | Male | 5 | No | Yes | 86 | 3 | 84 | 12 | 87 | 10 | 102 | 12 |

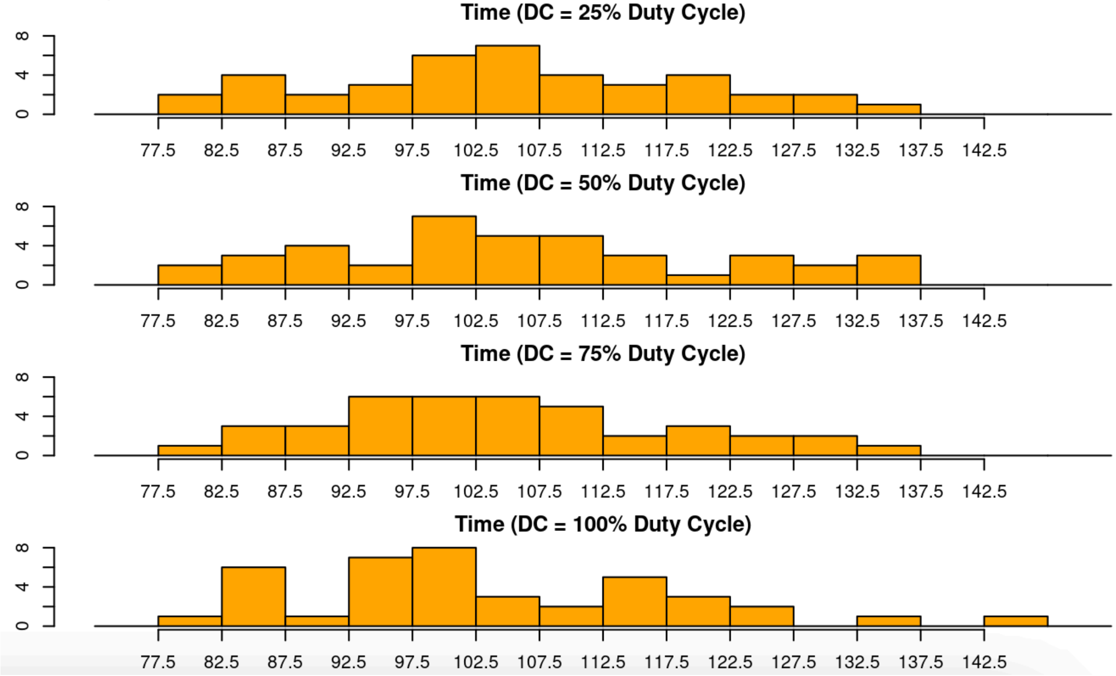
| Participant # | Age | Gender | English | EyeWear | 20/20 Vision | 25 Time | 25 Mistakes | 50 Time | 50 Mistakes | 75 Time | 75 Mistakes | 100 Time | 100 Mistakes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **21** | 22 | Male | 4 | Yes | Yes | 132 | 3 | 132 | 8 | 134 | 2 | 144 | 4 |
| **22** | 22 | Female | 4 | Yes | Yes | 109 | 4 | 107 | 6 | 107 | 7 | 114 | 5 |
| **23** | 22 | Female | 5 | No | Yes | 83 | 2 | 85 | 9 | 94 | 3 | 112 | 3 |
| **24** | 21 | Male | 5 | No | Yes | 79 | 5 | 79 | 4 | 85 | 4 | 93 | 3 |
| **25** | 29 | Male | 4 | No | Yes | 106 | 9 | 95 | 3 | 98 | 6 | 81 | 16 |
| **26** | 25 | Male | 4 | No | Yes | 99 | 2 | 99 | 3 | 101 | 2 | 96 | 1 |
| **27** | 25 | Male | 3 | No | Yes | 125 | 16 | 128 | 14 | 124 | 13 | 130 | 17 |
| **28** | 21 | Female | 5 | Yes | Yes | 101 | 5 | 100 | 8 | 99 | 6 | 101 | 5 |
| **29** | 24 | Female | 5 | No | Yes | 116 | 7 | 102 | 9 | 111 | 13 | 105 | 10 |
| **30** | 21 | Female | 4 | Yes | Yes | 124 | 18 | 123 | 11 | 124 | 11 | 121 | 19 |
| **31** | 23 | Female | 5 | Yes | Yes | 103 | 8 | 114 | 4 | 100 | 4 | 99 | 3 |
| **32** | 32 | Male | 3 | No | Yes | 109 | 3 | 105 | 5 | 91 | 2 | 99 | 2 |
| **33** | 32 | Male | 3 | Yes | Yes | 116 | 5 | 134 | 6 | 125 | 11 | 115 | 7 |
| **34** | 22 | Female | 4 | Yes | Yes | 76 | 15 | 97 | 11 | 99 | 14 | 84 | 12 |
| **35** | 21 | Female | 4 | No | Yes | 109 | 11 | 130 | 13 | 115 | 10 | 119 | 10 |
| **36** | 20 | Male | 5 | Yes | Yes | 117 | 4 | 112 | 5 | 111 | 4 | 108 | 3 |
| **37** | 18 | Female | 5 | No | Yes | 93 | 13 | 88 | 8 | 97 | 6 | 84 | 9 |
| **38** | 18 | Female | 5 | No | Yes | 114 | 5 | 108 | 4 | 107 | 21 | 111 | 3 |
| **39** | 18 | Female | 5 | No | Yes | 102 | 11 | 99 | 9 | 108 | 9 | 90 | 7 |
| **40** | 18 | Female | 5 | Yes | Yes | 83 | 4 | 88 | 2 | 99 | 2 | 84 | 6 |

## G. STATISTICAL ANALYSES

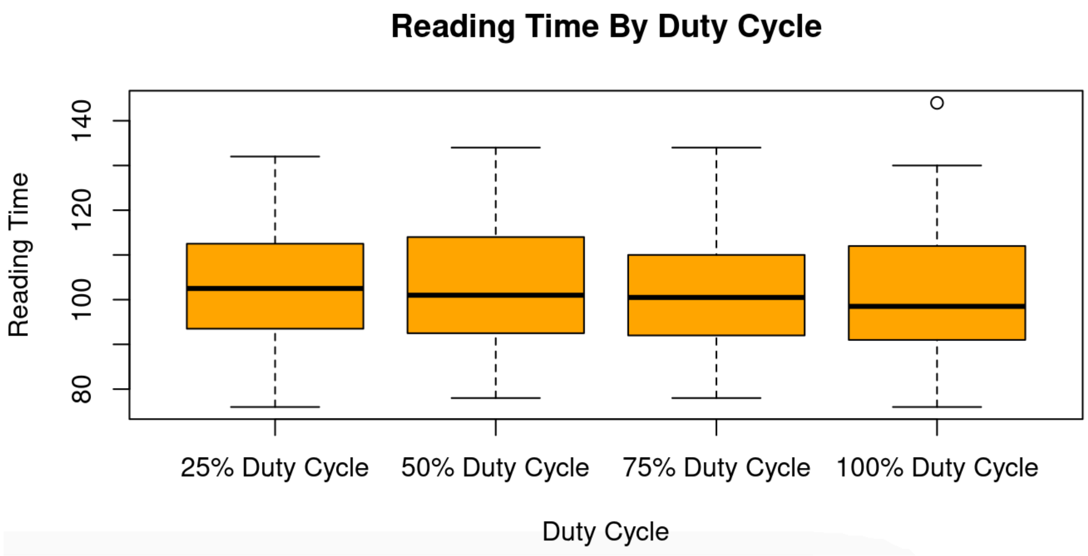
### Hypothesis 1

```
# Startup Code
require(lolcat)
require(car)
require(dplyr)
require(sjstats)
require(flextable)
require(tibble)
options(scipen=99,digits = 10)
options(show.signif.stars=FALSE)   # Turn off * to indicate significance
nqtr <- function(x,d){noquote(t(round.object(x, d)))}
ro <- round.object

# Step 1: Information ----------------------------------------------------------------
# Marianna Benitez
# The Effect of LED Pulse-Width Modulation of Light on Visual Performance
# What is the effect of LED duty cycle on reading time?

# Step 2: Dependent Variable Information -----------------------------------
# Criterion measure: reading time [s]
# Scale of measurement: continuous - ratio
# Performance criterion: smaller is better

# Import data
View(Data)
n<-40 # > 25
```

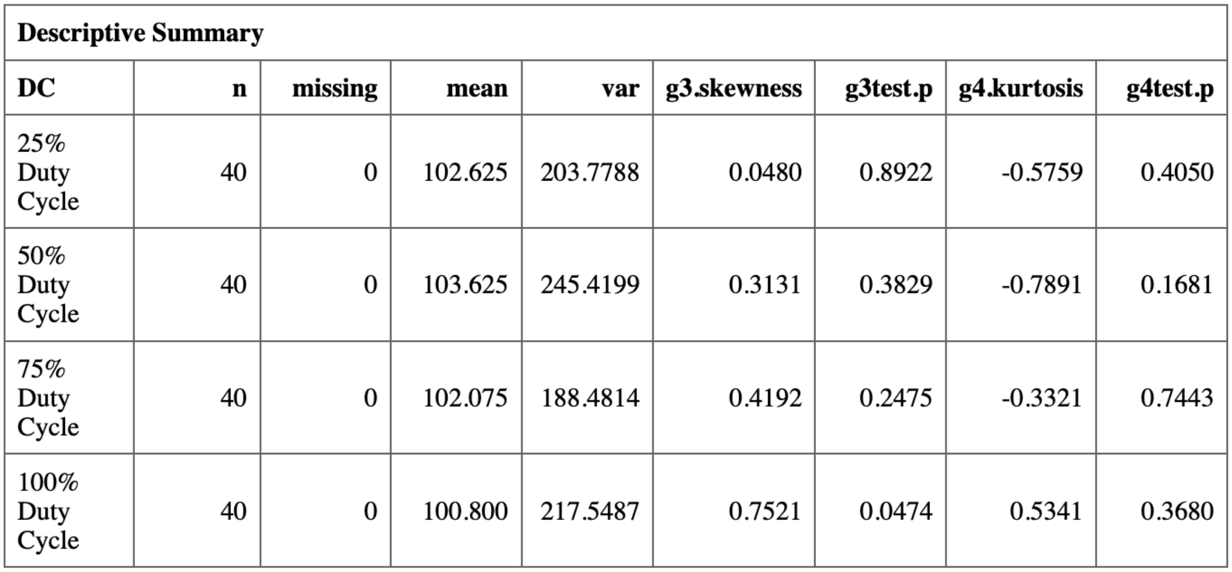
```
# Specify factors with labels
# J = 4 levels, 3 degrees of freedom
group.labels<-c("25% Duty Cycle","50% Duty Cycle","75% Duty Cycle","100% Duty Cycle")
Data$DC<-factor(Data$DC,labels=group.labels)
str(Data)

# Descriptive summary
process.group.plot(fx=Time~DC, data=Data, col="orange")
dev.off()
```



```
boxplot(Time~DC,data=Data,xlab="Duty Cycle", ylab="Reading Time", main="Reading Time By Duty Cycle", col="orange")
```



```
so<-ro(summary.continuous(Time~DC,Data),4)

so %>%

  flextable() %>%

  add_header_lines(values = "Descriptive Summary") %>%

  theme_box()
```

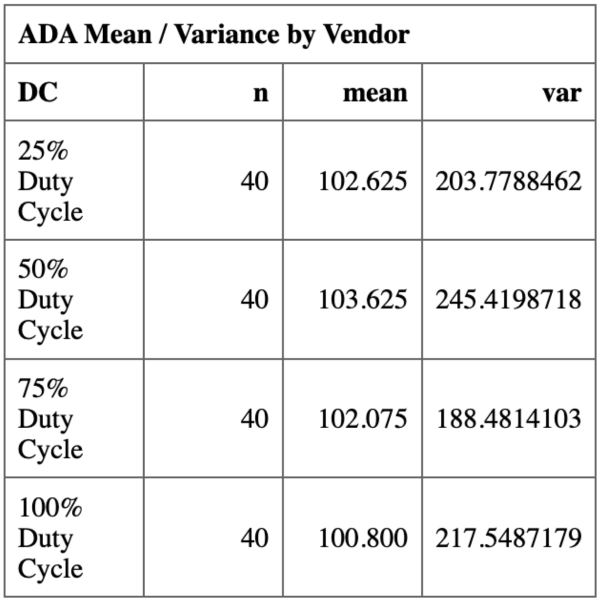


| **Descriptive Summary** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **DC** | **n** | **missing** | **mean** | **var** | **g3.skewness** | **g3test.p** | **g4.kurtosis** | **g4test.p** |
| 25% Duty Cycle | 40 | 0 | 102.625 | 203.7788 | 0.0480 | 0.8922 | -0.5759 | 0.4050 |
| 50% Duty Cycle | 40 | 0 | 103.625 | 245.4199 | 0.3131 | 0.3829 | -0.7891 | 0.1681 |
| 75% Duty Cycle | 40 | 0 | 102.075 | 188.4814 | 0.4192 | 0.2475 | -0.3321 | 0.7443 |
| 100% Duty Cycle | 40 | 0 | 100.800 | 217.5487 | 0.7521 | 0.0474 | 0.5341 | 0.3680 |

```
# Step 3: Statistical Hypothesis ----------------------------------------

# Ho: If the duty cycle is 25% (the smallest), then reading time will be the largest

# H1: Not Ho
```

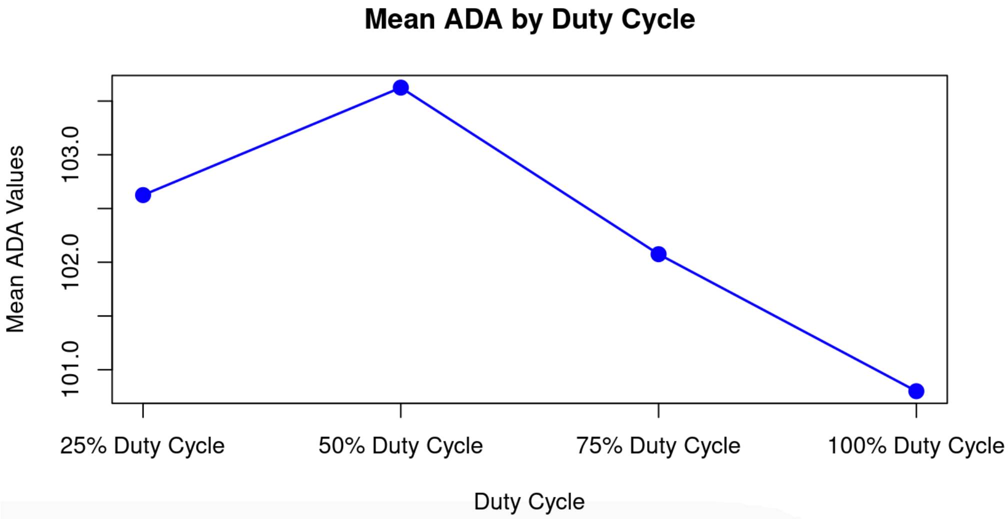
```
# Step 4: Select Statistical Test ---------------------------------------------
# 1. Skewness and Kurtosis Test
# 2. ADA Levene Test
# 3. Tukey HSD

# Step 5: Consider Type 1 and 2 Errors ----------------------------------
# Type 1: alpha = 0.05
alpha<-0.05
conf<-1-alpha
# Rejecting H0 when it is True, leads to concluding that the duty cycle does not
impact reading time or that the levels of duty cycle values have no difference on the
reading time.

# Type 2: beta = 0.1
# Failing to Reject H0 when it is False would lead to the conclusion that lower duty
cycle values negatively impact reading time.

# Step 6: Validate Underlying Assumptions --------------------------------
# Normally distributed
# Equal variances
# Independent and randomly drawn = yes

# Step 7: Perform Statistical Test --------------------------------------
# Ho: gamma3 and gamma4 = 0 = normally distributed
so<-ro(summary.continuous(Time~DC,Data),4)
# 25% g3test.p = 0.8922, g4test.p = 0.4050 > alpha
# 50% g3test.p = 0.3829, g4test.p = 0.1681 > alpha
```

```
# 75% g3test.p = 0.2475, g4test.p = 0.7443 > alpha
# 100% g3test.p = 0.0474 about >= alpha, g4test.p = 0.3680 > alpha

# Ho: All variances are equal
# Absolute Deviation from the Average (ADA), use if normal
Data$ADATime<-compute.group.dispersion.ADA(fx=Time~DC,data=Data)
DataADA.aov<-aov(formula=Time~DC,data=Data)

# ADA is new DV ~ IV
(sourcetableADA.aov<-summary(DataADA.aov))
# Residual represents within group variability
# If there is no difference, between group variability is similar to within
# p-value = Pr(>F) = 0.85451 > 0.05 so fail to reject Ho, there is no difference

# 1. Table of ADA means by group
(ada.means.var<-
summary.impl(fx=Time~DC,data=Data,stat.n=TRUE,stat.mean=TRUE,
                              stat.var=TRUE))

# Table of Means and Variance of ADA
ada.means.var %>%
  flextable() %>%
  add_header_lines(values = "ADA Mean / Variance by Vendor") %>%
  theme_box()
```



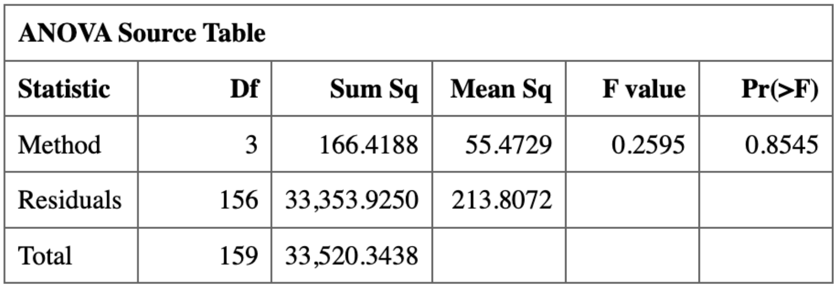
| ADA Mean / Variance by Vendor | | | |
|---|---:|---:|---:|
| **DC** | **n** | **mean** | **var** |
| 25% Duty Cycle | 40 | 102.625 | 203.7788462 |
| 50% Duty Cycle | 40 | 103.625 | 245.4198718 |
| 75% Duty Cycle | 40 | 102.075 | 188.4814103 |
| 100% Duty Cycle | 40 | 100.800 | 217.5487179 |

```
# 2. Line plot
plot(ada.means.var$mean,xaxt="n",type="o",lty=1,pch=19,cex = 1.3,lwd= 1.7,
    col="blue",xlab="Duty Cycle",ylab="Mean ADA Values",
    main = "Mean ADA by Duty Cycle")
axis(1, at=1:4, labels=group.labels)
```



```
# Ho: All means are equal
Data.aov<-aov(formula=Time~DC,data=Data)
(sourcetable.aov<-summary(Data.aov))  # Display and Save the ANOVA (Summary)
Source Table
```

```
# p-value = Pr(>F) = 0.8541 > 0.05 so fail to reject Ho, there is no difference


# Add Totals to ANOVA Table
(anova.temp<-sourcetable.aov[[1]])
totaldf<-sum(anova.temp$Df)
totalss<-sum(anova.temp$`Sum Sq`)
total<-data.frame(totaldf, totalss,"","","")
names(total)<-c("Df","Sum Sq","Mean Sq","F value","Pr(>F)")
(anova.out<-rbind(anova.temp,as.numeric(total)))
rownames(anova.out)<-c("Method","Residuals","Total")


anova.out %>%
  tibble::rownames_to_column(var = "Statistic") %>%
  flextable() %>%
  add_header_lines(values = "ANOVA Source Table") %>%
  colformat_double(j=c('Sum Sq','Mean Sq', 'F value', 'Pr(>F)'), digits=4, na_str = '')
%>%
  theme_box()
```



**ANOVA Source Table**

| Statistic | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
|---|---:|---:|---:|---:|---:|
| Method | 3 | 166.4188 | 55.4729 | 0.2595 | 0.8545 |
| Residuals | 156 | 33,353.9250 | 213.8072 | | |
| Total | 159 | 33,520.3438 | | | |

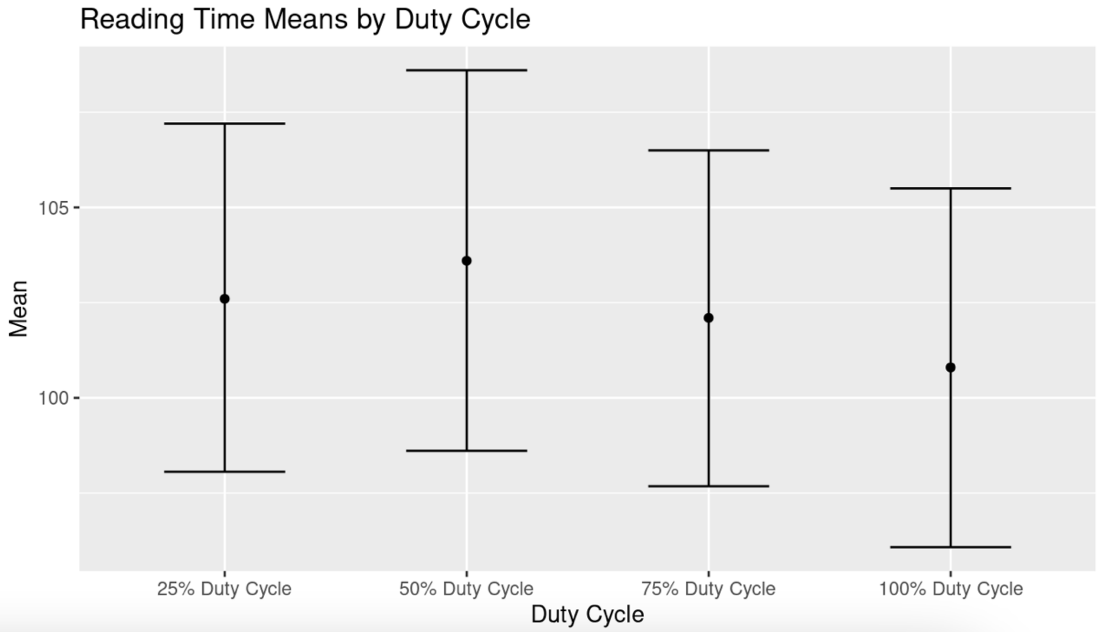
```
# Step 8: Statistical Conclusion -----------------------------------------
# Define the Anova model
model<-lm(formula=Time~DC,data=Data)
anova.stats<-anova_stats(model, digits = 4) #sjstats package
```

```
anova.stats$omegasq[1] # means -1.41% importance, only report when reject Ho
```

```
# Compute and save factor level n, means and variances
(mean.var<-ro(summary.impl(fx=Time~DC, data=Data, stat.n=TRUE,
stat.mean=TRUE, stat.var=TRUE),4))
```

```
require(rcompanion)
(sum.out<-groupwiseMean(formula=Time~DC,data=Data,conf=conf,digits=4))
                DC  n  Mean Conf.level Trad.lower Trad.upper
1  25% Duty Cycle 40 102.6       0.95      98.06      107.2
2  50% Duty Cycle 40 103.6       0.95      98.61      108.6
3  75% Duty Cycle 40 102.1       0.95      97.68      106.5
4 100% Duty Cycle 40 100.8       0.95      96.08      105.5
```

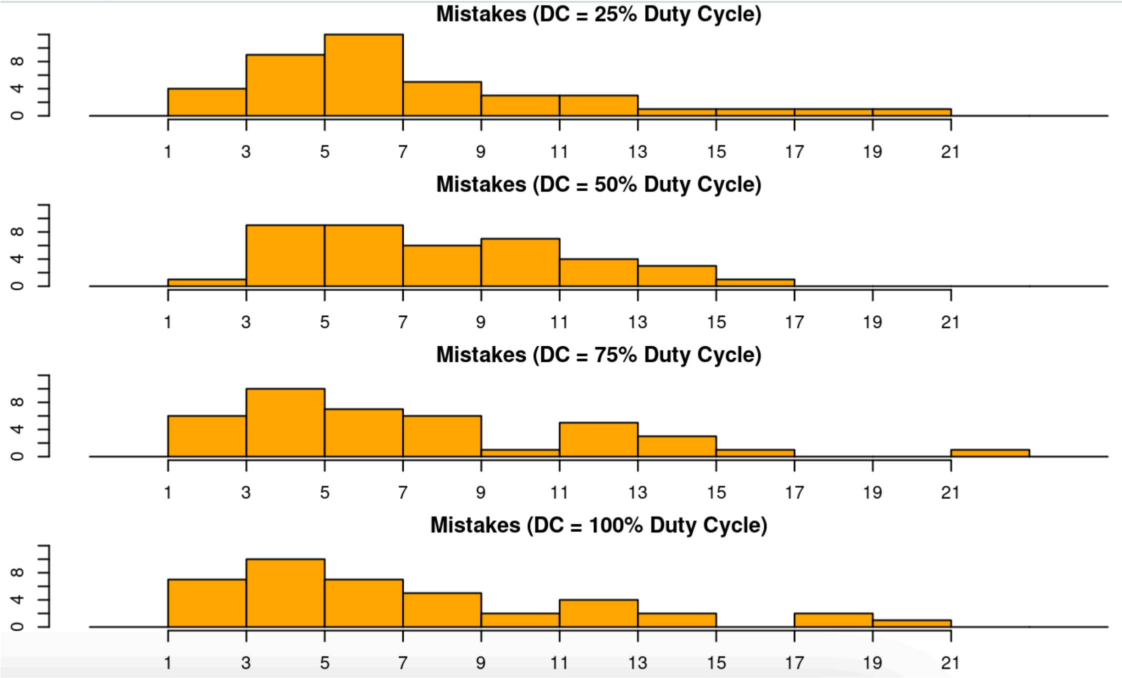
```
require(ggplot2)
(Data.plot<-qplot(x=DC,y=Mean,data=sum.out,xlab="Duty Cycle",
          main="Reading Time Means by Duty Cycle") +
 geom_errorbar(aes(ymin=Trad.lower,ymax=Trad.upper,width=0.5)))
```



Hypothesis 2

```
# Startup Code
require(lolcat)
require(car)
require(dplyr)
require(sjstats)
require(flextable)
require(tibble)
options(scipen=99,digits = 10)
options(show.signif.stars=FALSE)   # Turn off * to indicate significance
nqtr <- function(x,d){noquote(t(round.object(x, d)))}
ro <- round.object

# Step 1: Information -----------------------------------------------------------
# Marianna Benitez
# The Effect of LED Pulse-Width Modulation of Light on Visual Performance
# What is the effect of LED duty cycle on reading time?

# Step 2: Dependent Variable Information ----------------------------------
# Criterion measure: reading time [s]
# Scale of measurement: continuous - ratio
# Performance criterion: smaller is better

# Import data
View(Data)
n<-40 # > 25
```

```
# Specify factors with labels
# J = 4 levels, 3 degrees of freedom
group.labels<-c("25% Duty Cycle","50% Duty Cycle","75% Duty Cycle","100% Duty Cycle")
Data$DC<-factor(Data$DC,labels=group.labels)
str(Data)


# Descriptive summary
process.group.plot(fx=Mistakes~DC, data=Data,col="orange")
dev.off()
```



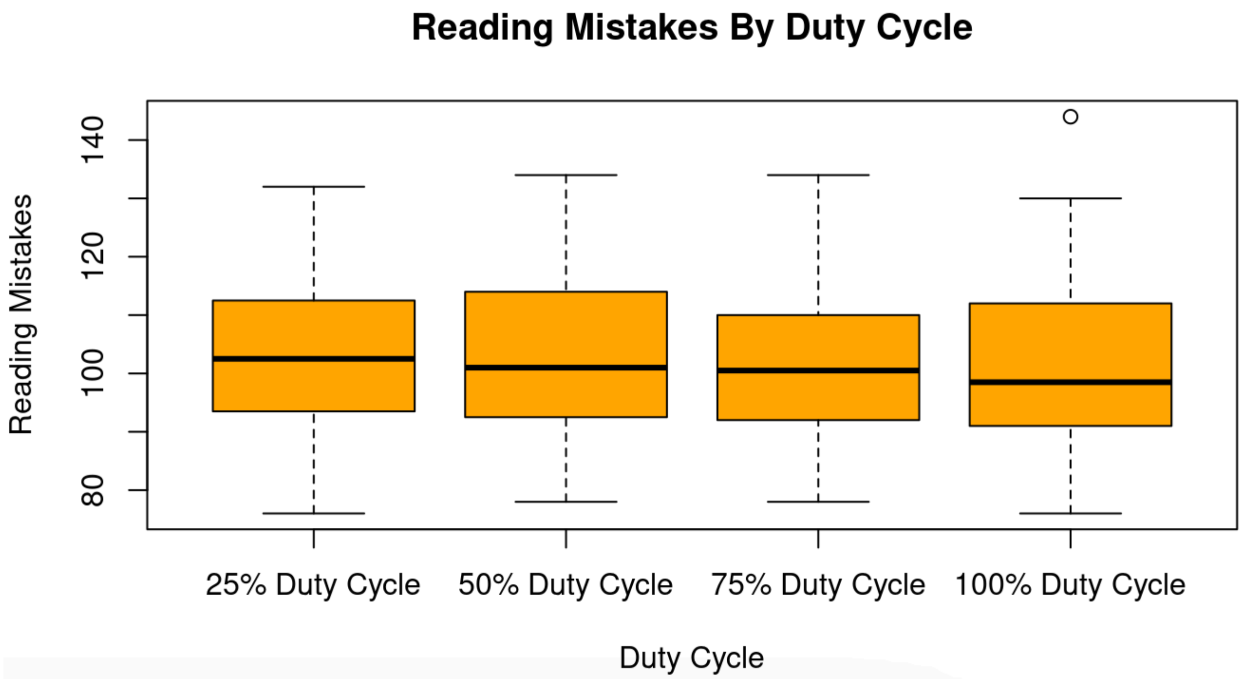
Mistakes (DC = 25% Duty Cycle)

Mistakes (DC = 50% Duty Cycle)

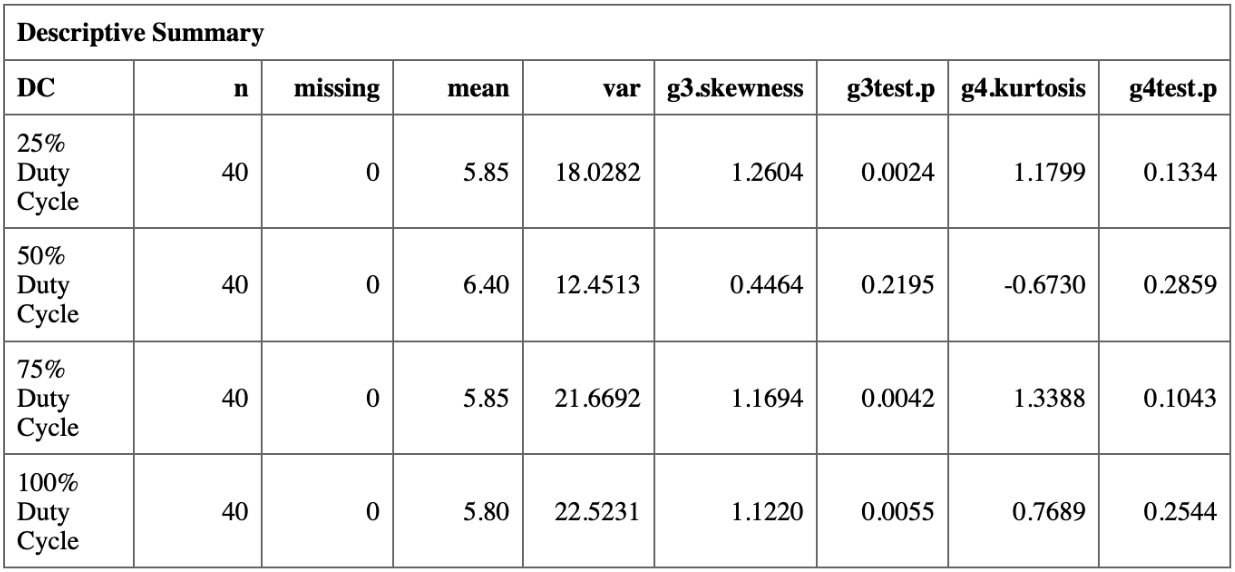
Mistakes (DC = 75% Duty Cycle)

Mistakes (DC = 100% Duty Cycle)

```
boxplot(Time~DC,data=Data,xlab="Duty Cycle", ylab="Reading Mistakes",
        main="Reading Mistakes By Duty Cycle", col="orange")
```



```
so<-ro(summary.continuous(Mistakes~DC,Data),4)
so %>%
  flextable() %>%
  add_header_lines(values = "Descriptive Summary") %>%
  theme_box()
```



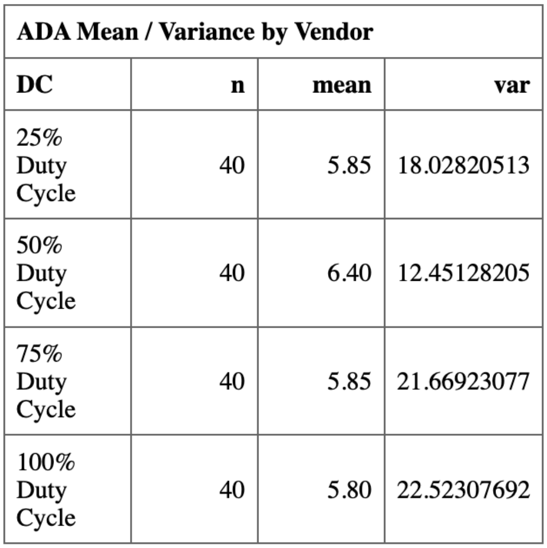
| Descriptive Summary | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **DC** | **n** | **missing** | **mean** | **var** | **g3.skewness** | **g3test.p** | **g4.kurtosis** | **g4test.p** |
| 25% Duty Cycle | 40 | 0 | 5.85 | 18.0282 | 1.2604 | 0.0024 | 1.1799 | 0.1334 |
| 50% Duty Cycle | 40 | 0 | 6.40 | 12.4513 | 0.4464 | 0.2195 | -0.6730 | 0.2859 |
| 75% Duty Cycle | 40 | 0 | 5.85 | 21.6692 | 1.1694 | 0.0042 | 1.3388 | 0.1043 |
| 100% Duty Cycle | 40 | 0 | 5.80 | 22.5231 | 1.1220 | 0.0055 | 0.7689 | 0.2544 |

```
# Step 3: Statistical Hypothesis ----------------------------------------
```

```
# Ho: If the duty cycle is 25% (the smallest), then reading mistakes will be the
largest
# H1: Not Ho

# Step 4: Select Statistical Test ------------------------------------------------
# 1. Skewness and Kurtosis Test
# 2. ADA Levene Test
# 3. Tukey HSD

# Step 5: Consider Type 1 and 2 Errors ------------------------------------
# Type 1: alpha = 0.05
alpha<-0.05
conf<-1-alpha
# Rejecting H0 when it is True, leads to concluding that the duty cycle does not
impact reading time or that the levels of duty cycle values have no difference on the
reading time.

# Type 2: beta = 0.1
# Failing to Reject H0 when it is False would lead to the conclusion that lower duty
cycle values negatively impact reading time.

# Step 6: Validate Underlying Assumptions ---------------------------------
# Normally distributed
# Equal variances
# Independent and randomly drawn = yes

# Step 7: Perform Statistical Test ----------------------------------------
```

```
# Ho: gamma3 and gamma4 = 0 = normally distributed
so<-ro(summary.continuous(Mistakes~DC,Data),4)
# 25% g3test.p = 0.0024 < alpha, g4test.p = 0.1334 > alpha
# 50% g3test.p = 0.2195, g4test.p = 0.2859 > alpha
# 75% g3test.p = 0.0042 < alpha, g4test.p = 0.1043 > alpha
# 100% g3test.p = 0.0055 < alpha, g4test.p = 0.2544 > alpha
# so<-ro(summary.continuous((Mistakes/Time)~DC,Data),4)
# process.group.plot(Mistakes/Time~DC,data=Data)
# Repeated measures ANOVA


# Ho: All variances are equal
# Absolute Deviation from the Average (ADA), use if normal
Data$ADAMistakes<-
compute.group.dispersion.ADA(fx=Mistakes/Time~DC,data=Data)
DataADA.aov<-aov(formula=Mistakes/Time~DC,data=Data)

# ADA is new DV ~ IV
(sourcetableADA.aov<-summary(DataADA.aov))
# Residual represents within group variability
# If there is no difference, between group variability is similar to within
# p-value = Pr(>F) = 0.9290 > 0.05 so fail to reject Ho, there is no difference

# 1. Table of ADA means by group
(ada.means.var<-summary.impl(fx=Mistakes~DC,data=Data,stat.n=TRUE,
                    stat.mean=TRUE,stat.var=TRUE))
```

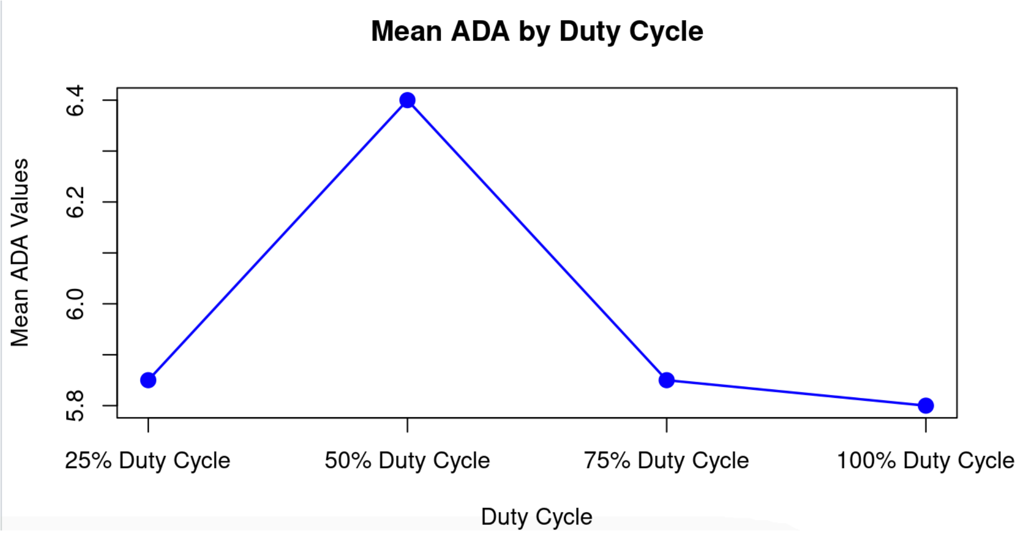
```
# Table of Means and Variance of ADA
ada.means.var %>%
  flextable() %>%
  add_header_lines(values = "ADA Mean / Variance by Vendor") %>%
  theme_box()
```



**ADA Mean / Variance by Vendor**

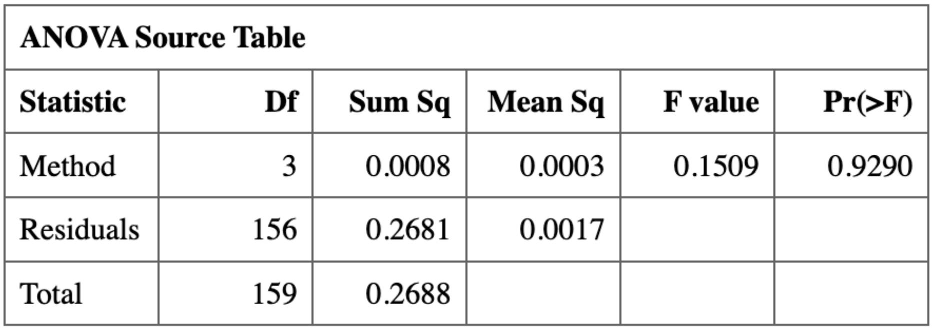
| DC | n | mean | var |
|---|---|---|---|
| 25% Duty Cycle | 40 | 5.85 | 18.02820513 |
| 50% Duty Cycle | 40 | 6.40 | 12.45128205 |
| 75% Duty Cycle | 40 | 5.85 | 21.66923077 |
| 100% Duty Cycle | 40 | 5.80 | 22.52307692 |

```
# 2. Line plot
plot(ada.means.var$mean,xaxt="n",type="o",lty=1,pch=19,cex = 1.3,lwd= 1.7,
     col="blue",xlab="Duty Cycle",ylab="Mean ADA Values",
     main = "Mean ADA by Duty Cycle")
axis(1, at=1:4, labels=group.labels)
```



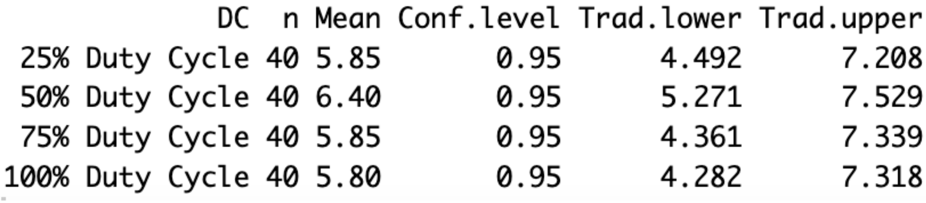
```
# Ho: All means are equal

Data.aov<-aov(formula=Mistakes/Time~DC,data=Data)

(sourcetable.aov<-summary(Data.aov))  # Display and Save the ANOVA (Summary)
Source Table

# p-value = Pr(>F) = 0.9290 > 0.05 so fail to reject Ho, there is no difference


# Add Totals to ANOVA Table

(anova.temp<-sourcetable.aov[[1]])

totaldf<-sum(anova.temp$Df)

totalss<-sum(anova.temp$`Sum Sq`)

total<-data.frame(totaldf, totalss,"","","")

names(total)<-c("Df","Sum Sq","Mean Sq","F value","Pr(>F)")

(anova.out<-rbind(anova.temp,as.numeric(total)))

rownames(anova.out)<-c("Method","Residuals","Total")


anova.out %>%

  tibble::rownames_to_column(var = "Statistic") %>%

  flextable() %>%
```

```
  add_header_lines(values = "ANOVA Source Table") %>%
  colformat_double(j=c('Sum Sq','Mean Sq', 'F value', 'Pr(>F)'), digits=4, na_str = '')
%>%
  theme_box()
```



| ANOVA Source Table | | | | | |
|---|---|---|---|---|---|
| **Statistic** | **Df** | **Sum Sq** | **Mean Sq** | **F value** | **Pr(>F)** |
| Method | 3 | 0.0008 | 0.0003 | 0.1509 | 0.9290 |
| Residuals | 156 | 0.2681 | 0.0017 | | |
| Total | 159 | 0.2688 | | | |

```
# Step 8: Statistical Conclusion -----------------------------------------
# Define the Anova model
model<-lm(formula=Mistakes~DC,data=Data)
anova.stats<-anova_stats(model, digits = 4) #sjstats package
anova.stats$omegasq[1] # means -1.57% importance


# Compute and save factor level n, means and variances
(mean.var<-ro(summary.impl(fx=Mistakes~DC,data=Data,stat.n=TRUE,
                        stat.mean=TRUE,stat.var=TRUE),4))


require(rcompanion)
(sum.out<-groupwiseMean(formula=Mistakes~DC,data=Data,conf=conf,
                  digits=4))
```



```
               DC  n Mean Conf.level Trad.lower Trad.upper
  25% Duty Cycle 40 5.85       0.95      4.492      7.208
  50% Duty Cycle 40 6.40       0.95      5.271      7.529
  75% Duty Cycle 40 5.85       0.95      4.361      7.339
 100% Duty Cycle 40 5.80       0.95      4.282      7.318
```

```
require(ggplot2)
```

```
Data.plot<-qplot(x=DC,y=Mean,data=sum.out,xlab="Duty Cycle",
            main="Reading Mistake Means by DC") +
 geom_errorbar(aes(ymin=Trad.lower,ymax=Trad.upper,width=0.5))
(Data.plot)
```