Lux junior 2024

17. Internationales Forum für den lichttechnischen Nachwuchs
Ilmenau, 6. – 8. September 2024
DOI (proceedings): 10.22032/dbt.61636

DOI: 10.22032/dbt.xxxxx

The visibility of stroboscopic effects in individuals with myopia

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Abstract

This study investigates how myopia affects the visibility thresholds of stroboscopic effects, which are visual phenomena caused by the pulse width modulation (PWM) of LEDs. These effects can be intensified by improper operational parameter settings. Through visual experiments with myopic participants, this study examines how these effects vary under different parameters. We used a modulated LED light source with a 4500 K correlated color temperature to illuminate a rotating black disk with a white dot. The LED modulation was controlled by a square waveform with frequencies from 100 Hz to 4200 Hz and various duty cycles. Participants perceived stroboscopic effects at a speed of 4 m/s and an illuminance of 500 lx. Using the method of constant stimuli, we identified 50 percent detection thresholds under various conditions.

Based on our experimental setup and data analysis, this study introduces a model that characterizes the relationship between absolute visibility thresholds and duty cycles for myopic individuals. The model demonstrates its predictive capability by extrapolating thresholds based on data obtained from the 10 % duty cycle. These results provided valuable information for the design of luminaires avoiding stroboscopic effects, particularly for those with myopia.

Index Terms: LEDs, PWM, stroboscopic effects, myopia vision

1 Introduction

Light-emitting diodes (LEDs) have gained popularity due to their long operational lifespans and energy efficiency compared to traditional lighting sources like incandescent and fluorescent lamps [1]. A notable advantage of LEDs is their rapid response to changes in driving current, which makes them particularly suitable for pulse width modulation (PWM) applications, such as LED dimming. PWM dimming allows precise control of LED brightness with minimal chromaticity shift, offering a more visually stable experience compared to constant current dimming methods [2, 3]. However, PWM dimming also introduces potential issues like Temporal Light Artifacts (TLAs), including flicker and stroboscopic effects. These artifacts can cause visual discomfort during eye movements or when viewing moving objects, posing potential health risks [4 - 7]. Short-term exposure to TLAs can trigger epileptic-sensitive photo spasms [8, 9], while long-term exposure may lead to headaches, migraines, and impaired visual performance [10, 11, 12]. While most individuals cannot perceive flicker beyond 100 Hz [13]. Berman et al. suggest that light modulation may be transmitted through the retina at frequencies up to 200 Hz [14].

In the area of vision science, understanding how different populations perceive stroboscopic effects is crucial for designing lighting systems that mitigate these adverse impacts. Among these populations, individuals with myopia, represent a significant group whose unique visual characteristics warrant focused study. Myopia is a common refractive error where distant objects appear blurry due to the elongation of the eyeball or the steepness of the cornea [15]. This condition affects a substantial portion of the global population and is particularly prevalent in urbanized areas and among younger humans [16]. The visual perception of individuals with myopia differs in several key aspects from those with normal vision. Myopic individuals often exhibit reduced contrast sensitivity and altered accommodative responses, which can influence their perception of dynamic visual stimuli such as stroboscopic effects induced by PWM [17,18]. Consequently, myopic vision may interact uniquely with stroboscopic effects, potentially exacerbating or modifying the perception of these visual artefacts.

Stroboscopic effects occur when observers perceive multiple discrete images of a moving object rather than smooth motion. Research has shown that the visibility of stroboscopic effects depends on several parameters, including frequency, modulation depth, and duty cycle [19 - 23]. Studies have demonstrated that the perception of these effects varies not only with frequency but also with object speed and environmental conditions. For example, Bullough et al. found that both frequency and modulation depth interact significantly in determining the visibility of stroboscopic effects [20 - 22]. To define a suitable metric for the Stroboscopic Effect, Perz and Wang et al. [9,24] conducted a study consisting of three experiments. These experiments formed the basis for the development of the Stroboscopic Effect Visibility Measure (SVM) and demonstrated the validity of this newly proposed metric. They emphasized that the

SVM was determined under typical office conditions - illuminance around 500 lx and an object speed of the disk at 4 m/s. Recognizing the need for broader validation, they called for investigations about the measure changes for different illuminance levels and the speeds of object movements, such as dimmer environments (e.g., street lighting) and faster object movements (e.g., sports and industrial settings with rapidly rotating machinery) [25]. The Commission of the European Union also adopted the SVM metric and defined SVM = 0.4 [26].

To accurately assess the stroboscopic effect in myopic individuals, it is essential to consider these unique visual characteristics. Prior research, such as the work of Chen and Brown [17], has shown that myopia reduces contrast sensitivity, while studies by Charman and Radhakrishnan highlight distinct visual processing traits in myopic individuals [18]. These findings underscore the need for tailored lighting solutions that accommodate the specific visual needs of this population.

This paper aims to bridge the knowledge gap regarding the stroboscopic effect in myopic individuals by developing an objective model to predict visibility thresholds. Through targeted perception experiments and data analysis, we aim to explore the relationship between absolute visibility thresholds and duty cycles in myopic vision. The insights gained from this research will enhance our theoretical understanding and inform the design of lighting systems that improve visual comfort and performance for individuals with myopia [27].

2 Experimental Methods

2.1 Apparatus

The experiments used a rotating disk with a 25 cm diameter, featuring a white spot of 15 mm diameter on a black cotton surface, as shown in Figure 1. This setup provided a significant contrast between moving targets and backgrounds. The white spot was placed 10.5 cm from the center and rotated at 4 m/s, suitable for studying stroboscopic effects in office settings [28]. The disk was positioned 76 cm above the floor, aligning with the height of a standard desk. The distance from the subject to the center of disk was maintained at approximately 68 cm, with a constant 66 cm distance between the eyes of subject and the stimulus, ensured by using a chin rest. The environment was completely dark with black walls and a tabletop covered in black cotton cloth to optimize visibility and minimize external influences.

As illustrated in Figure 2, the experimental setup included an LED light source with a correlated color temperature of 4500 K, detailed in Table 1. Here, A represents the white spot, B denotes the observation areas (see Fig. 1), and C refers to the remaining black areas. The LED illuminated the disk at 500 lx, driven by an LED driver supporting analog and PWM dimming methods. PWM signals were generated by an Agilent 33220A generator, allowing control over parameters such as frequency and duty cycle. The output was connected to the LED driver and powered by a Rohde & Schwarz

NGE100 power supply series at 5 V. A user interface in Python controlled the function generator, enabling variations in waveform type (sine, square), amplitude, frequency, and duty cycle.

Table 1. Selected test conditions at the illuminance levels of 500 lx for measuring the luminance of the various areas of the rotation disk, where A is the stimulus, B is the observation area and C is the remaining part of the disk.

	A	B	C
500 lx	75 cd/m^2	1.5 cd/m^2	0.001 cd/m^2

In conclusion, the experimental setup affords flexibility for modifying or adjusting fundamental parameters such as speeds, stimulus shapes, and stimulus sizes. Furthermore, it allows for the generation of square waveform signals with adjustable amplitude, duty cycle, and frequency. Different illuminance levels can be established, modified and maintained consistently within this experimental setup.

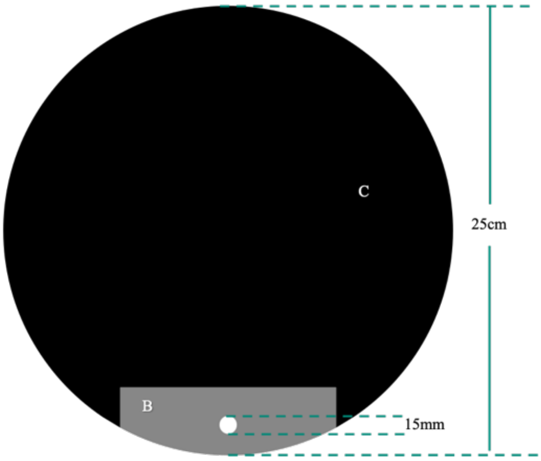


Figure 1. Top view of the rotation disk. A white dot was mounted on the positioned 10.5 cm from the center of the disk. The grey area (B) is the observation area of the experiment. The black area (C) is the remaining part of the disk in darkness.

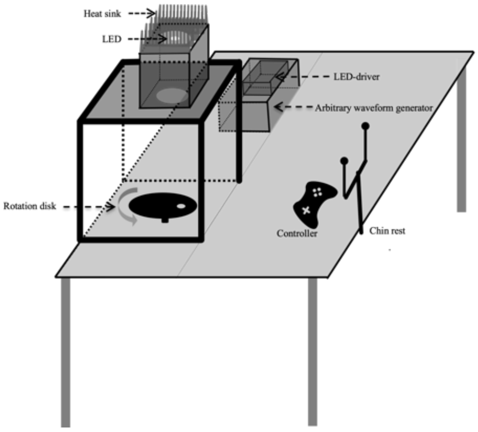


Figure 2. Picture (side view) of the experimental setup. The whole setup was installed in the darkened room. During the measurement, Observers put their chin on the chin rest, held the controller and looked at the rotation disk to detect the stroboscopic effects.

2.2 Procedure

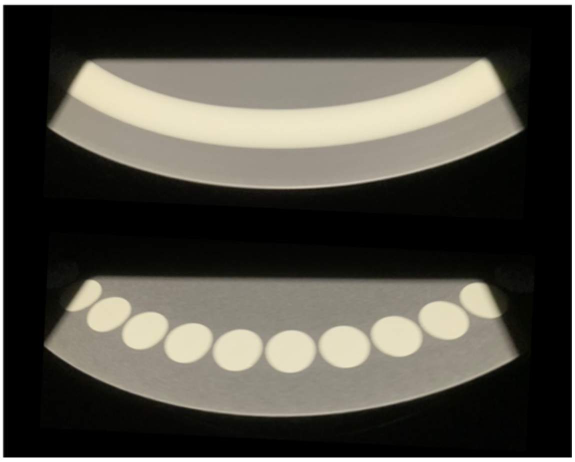
Participants sat 68 cm from the center of the disk, with a viewing angle of approximately 10.4 degrees as the white dot passed through the illuminated area. They received clear verbal instructions about the experimental procedure, including a comprehensive explanation of stroboscopic effects, supplemented by a brief practical demonstration to ensure familiarity. The disk rotated constantly throughout the experiment.

The experiment began with a 2-second DC light exposure. According to Perz et al., using a DC light as an initial stimulus improves accuracy and reduces variance. After the 2 seconds, the modulated light was automatically introduced. Participants were instructed to press the right controller key if they observed the stroboscopic effect on the rotating disk or the left key if they did not perceive it. The lights were turned off for 1 second after each input to signal that a new stimulus was about to follow. This process repeated until all modulated stimuli had been presented, and all responses of participants were recorded in a CSV file.

Using the method of constant stimuli, 50 percent detection thresholds were calculated for each condition. Figure 3 provides further insight by showing close-up images of the rotating disk under two lighting conditions: constant light without modulation, resulting in a blurred image, and modulated light, showing discrete movements of the spot due to stroboscopic effects.

The experiment aimed to detect stroboscopic effects while considering duty cycles as variable. Pre-experiments were conducted to determine an approximate threshold range between 100 Hz and 4200 Hz. The experimental procedure was divided into two phases: a low-resolution phase followed by a high-resolution test. The low-resolution phase used 17 frequency steps from 100 Hz to 4200 Hz with varying resolutions to estimate the threshold for the 50% duty cycle. The high-resolution test then refined the absolute threshold of the 50% duty cycle by measuring five values on either side of the estimated value. Using the model from the previous publication of the authors [34], estimated thresholds for 10%, 30%, 70%, and 80% duty cycles were derived from the 50% duty cycle absolute threshold. The absolute thresholds for these duty cycles were then established by measuring five values on either side of their respective estimated values. The LED was modulated with square waveform signals and different duty cycles (10%, 30%, 50%, 70%, 80%). Each stimulus was presented four times in random order at the object speeds of 4 m/s and the illuminance levels of 500 lx.

Each experimental condition took approximately 15 minutes per participant and was tested under two different conditions: with glasses and without. This approach allowed us to evaluate the effects of visual correction on stroboscopic perception. Participants had myopia ranging from -0.00 to -8.00 diopters, providing a broad spectrum of myopic severity for analysis. By comparing results under both conditions, we aimed to understand how varying diopters of myopia and the presence or absence of corrective lenses influence stroboscopic visibility thresholds.



Figures 3. Close-up pictures of the rotation disk under two different lighting conditions, the upper was under constant light with no modulation, and the lower was under modulated light, resulting in visible stroboscopic effects showing discrete movement of the dot.

3 Experimental Results

3.1 Effect of mild myopia

This experiment investigated how mild myopia affects the perception of stroboscopic effects. Data were collected from two groups: Group 'Previous', which included 24 participants (some with corrective glasses and some without) from prior research conducted by the authors, and Group 'Now', comprising 20 participants (all wearing corrective glasses) from the current study. The detection of stroboscopic effects is illustrated in Figure 4. Results indicate a decrease in absolute visibility thresholds across different duty cycles at an illuminance level of 500 lx and a speed of 4 m/s. The highest threshold was observed under the 10% duty cycle, while the lowest was under the 80% duty cycle.

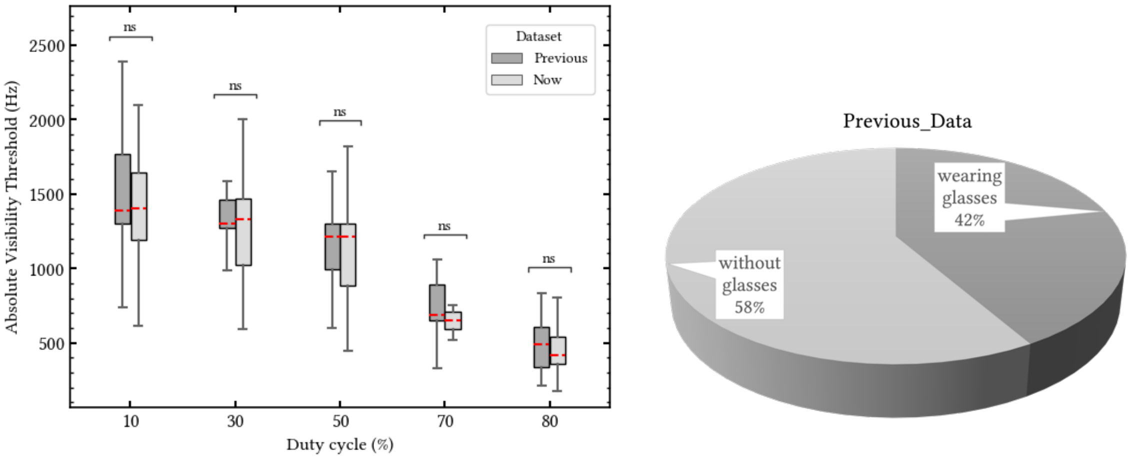


Figure 4. Boxplot (left) of the absolute visibility thresholds from two groups, one is 24 test persons (Group ‘Previous’) and the other is 20 test persons (Group ‘Now’). ‘ns’ represents no significance between the two groups. The medians are shown as red dashed. The pie chart (right) is based on 24 test persons from Group ‘Previous’, showing that 58% are without glasses and 42% wear glasses.

The horizontal line in each box corresponded to the 50th percentile (i.e., the median). These lower and upper borders of the box corresponded to the 25th and 75th percentiles, respectively. The whiskers indicated the total range in measured thresholds, excluding outliers (which are defined as deviating more than 1.5 times half the width of the box). Even though the variance of the conditions was different, an analysis of variance (ANOVA), a method used to test differences between two or more means resulting from parametric data, was performed to test for significant differences in the means of the conditions. At a significance level of $\alpha = 0.05$, no significant differences were found between the two groups at duty cycles.

In Group ‘Previous’, data collection involved test persons wearing glasses (42%) and those who did not (58%). It remains uncertain whether the 58% who did not wear glasses had normal vision or mild myopia that did not affect daily activities. The ANOVA results indicated no significant differences between Group ‘Previous’ and Group ‘Now’ under these conditions. This suggests that the absence of glasses in 58% of test persons did not impact absolute visibility thresholds. Variations in thresholds were attributed to individual sensitivity rather than uncertainty regarding the visual acuity of the 58% who did not wear glasses.

3.2 Comparison of myopia individuals with and without glasses

For all test persons with myopia, ranging from -0.00 to -8.00 diopters in Group ‘Now’, absolute visibility thresholds were measured both with (Group ‘Yes’) and without (Group ‘No’) glasses at the illuminance level of 500 lx and the speed of 4 m/s. Figure 5 shows the absolute visibility thresholds of the stroboscopic effect.

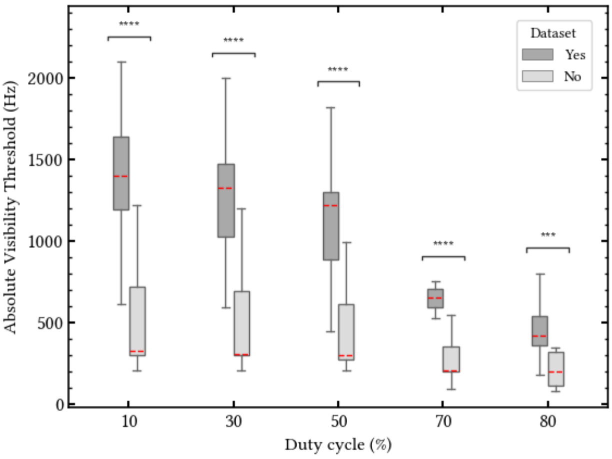


Figure 5. Boxplot of the absolute visibility thresholds of 20 test persons from Group ‘Now’. Yes represents wearing glasses and No represents without wearing glasses. star-marks (*) represent differences. The medians are shown as red dashed.

In different groups, the absolute visibility thresholds exhibited a consistent decreasing trend with an increasing duty cycle. However, the thresholds in Group ‘Yes’ were higher compared to those in Group 'No'. This indicates that myopia causes insensitivity to the detection of stroboscopic effects, resulting in lower thresholds. The ANOVA shows there are significant differences between both groups under each duty cycle at a significance level of $\alpha = 0.05$. For individuals with myopia, the absolute visibility thresholds varied depending on whether the glasses were worn. Specifically, participants with diopters ranging from -0.00 to -8.00 exhibited noticeable differences in detection thresholds between wearing glasses and not wearing them. The presence of corrective lenses generally improved sensitivity to stroboscopic effects.

Figure 6 (right) shows the distribution of diopters among the 20 participants, highlighting the range of myopic severity in the study. The participants' diopters range from mild to severe myopia, providing a comprehensive understanding of how myopic correction affects the perception of stroboscopic effects. The normalized visibility thresholds can be calculated using the formula (1):

$$Normalized\_Threshold = \frac{No_{abs\_threshold}}{Yes_{abs\_threshold}} \tag{1}$$

represent the ratio of absolute visibility thresholds without glasses to those with glasses. These thresholds are plotted as a function of the duty cycle in the line chart shown in Figure 6 (left). The analysis reveals a clear trend: the normalized visibility thresholds increase as the duty cycle increases. The lowest normalized thresholds occur at a 10% duty cycle, indicating that at this duty cycle, the relative difference in detection ability between wearing and not wearing glasses is greatest. This implies that myopic individuals are most sensitive to changes in duty cycles when corrective lenses are not used, particularly at lower duty cycles. Conversely, the highest normalized thresholds are observed at an 80% duty cycle, suggesting that the impact of corrective lenses on sensitivity diminishes as the duty cycle increases. This finding implies that corrective lenses have a more pronounced impact on enhancing visual sensitivity to stroboscopic effects at lower duty cycles. As duty cycles increase, the effect of glasses becomes less significant, potentially due to the increased visual persistence associated with higher duty cycles. These findings underscore the importance of considering both corrective eyewear and duty cycle settings when addressing stroboscopic visibility thresholds in individuals with myopia.

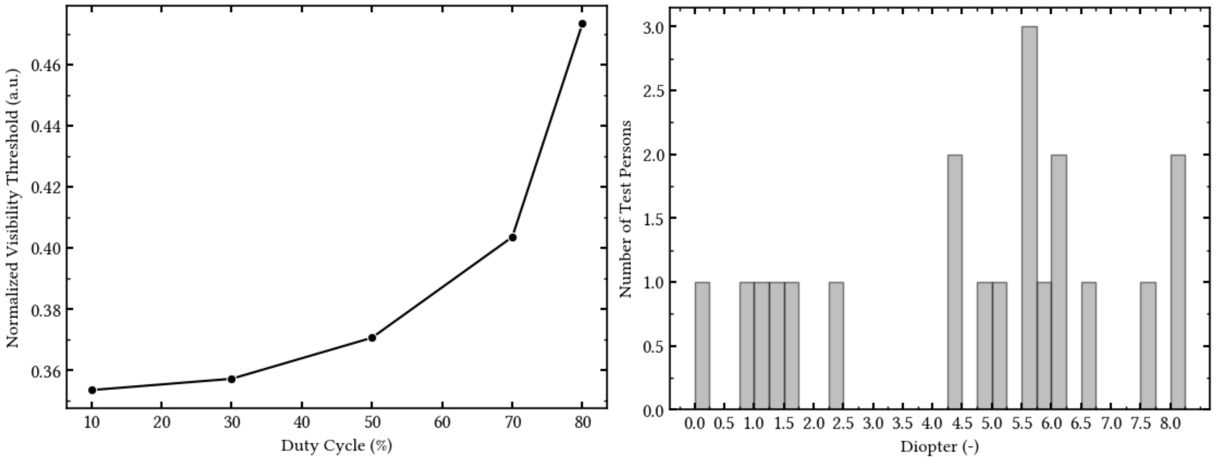


Figure 6. Left: Line chart illustrating the normalized visibility thresholds across different duty cycles, showing an increase in normalized thresholds as duty cycles increase. Right: Distribution of diopter values among the 20 participants.

3.3 Modeling duty cycle for uncorrected myopia

These absolute thresholds varied widely due to each individual subjectivity, using these values directly for analysis can result in an overemphasis on data with higher numerical levels while underemphasizing those with lower levers. Normalizing absolute thresholds proved to be a valuable step to enhance the reliability of the results.

In this experiment, the normalized thresholds are defined at the 10% duty cycle. We explored the stroboscopic effects and their correlation with the duty cycle. The normalized visibility thresholds of the stroboscopic effect were collected across 20 test persons without glasses from Group 'Now' at each duty cycle, and the results are shown in Figure 7. It is observed that the normalized visibility thresholds of the stroboscopic effect decrease as the duty cycle increases. Whiskers on the plot signify the error bars denoting standard deviation.

Based on these data, Equation (2) can be used to quantitatively describe this relationship, where $f(x)$ represents the normalized threshold, x represents the duty cycle and a, b are parameters.

$$f(x) = e^{ax^b} \tag{2}$$

To assess the effectiveness of the fit, the coefficient of determination (R^2) was computed with a value of 0.997, representing one minus the ratio of the sum of squares of the residuals to the total sum of squares. The results of R^2 elucidate that the variation in the normalized visibility thresholds is explicated by the duty cycle parameter. This robust R^2 compellingly supports the contention that the functional expression encapsulated in Equation (2) serves as a remarkably precise representation of the normalized visibility threshold about the duty cycle. Consequently, the model adeptly captures the intricate dynamics of this relationship, thereby affirming its efficacy in elucidating the observed variability with a high degree of fidelity.

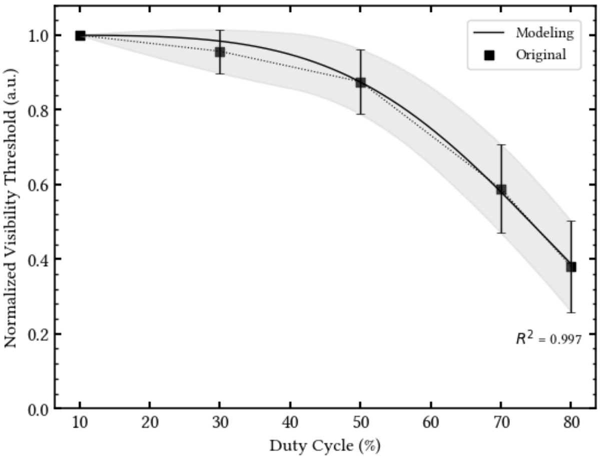


Figure 7. Modeling of the stroboscopic effects depending on duty cycle. Shown are the mean values of normalized thresholds with corresponding standard deviations and a coefficient of determination of R^2=0.997.

In summary, a model based on Equation (2) was developed, which considers the duty cycle. It is represented by Equation (3) and exhibited robust suitability across diverse parameter combinations. Where T_{abs} is the absolute visibility threshold, $T_{10\%\_abs}$ is absolute visibility threshold at 10% duty cycle.

$$T_{abs}(x) = \left(e^{ax^b}\right) * T_{10\%\_abs} \tag{3}$$

To conduct a comprehensive evaluation of the model's efficacy, we performed an error analysis. This error is derived by Equation (4).

$$error = \frac{predicted - absolute}{absolute} \tag{4}$$

Table 2 provides a comprehensive overview of the errors, presenting critical metrics for evaluating the performance of a model. The average error of 1.5% indicates that the predictions of the model are close to the true values, showing its overall accuracy and effectiveness. Furthermore, the standard deviation of 1.1% indicates that the errors tend to cluster closely around the average, implying consistent accuracy across diverse scenarios or observations and adding confidence in its reliability. While the maximum error of 2.8% indicates that significant deviations in predicted values are infrequent, they do occur occasionally. It is important to note that maximum errors are often outliers and may not be representative of the overall performance of the model. Nonetheless, knowing the maximum error provides insight into the model's potential limitations and can guide further improvements.

Table 2. Summary of modeling errors depending on the duty cycle at the illuminance level of 500 lx and the speed of 4 m/s. Shown is the overall average error for all experiments. E represents illuminance level, Avg represents average and SD represents standard deviation.

Duty cycle	10%	30%	50%	70%	80%	Avg (SD)
E = 500 lx Speed = 4 m/s	0%	2.8%	-0.1%	-1.5%	1.7%	1.5% (1.1%)

4 Discussion

These experiments aimed to develop a model for duty cycles that effectively predicts the visibility of the stroboscopic effect in individuals with myopia. While previous research, such as that conducted by Perz et al. [29], provided metrics for detecting stroboscopic effects in standard observers, there remains a gap in quantitative methods tailored for myopic individuals.

In the pre-experiment, we investigated different frequencies to identify the specific range at which the threshold occurs. The results indicated that the frequency range was between 100 Hz and 4200 Hz, providing a critical foundation for further studies on stroboscopic effect detection in myopic individuals. Analysis of the data reveals that the lowest normalized thresholds are observed at a 10% duty cycle, indicating that the greatest difference in stroboscopic effect detection when wearing glasses under this condition. Conversely, the highest normalized thresholds are found at an 80% duty cycle, suggesting that the benefit of wearing corrective lenses diminishes as the duty cycle increases.

These findings underscore the need for specialized metrics and models for myopic observers, as standard metrics may not fully capture the perception of stroboscopic effect in this population. Moreover, this research lays the groundwork for the development of more advanced models that incorporate duty cycle effects on stroboscopic visibility. By integrating these factors, we can enhance the accuracy of predictions related to stroboscopic effects, ultimately improving visual comfort and safety for individuals with myopia.

In summary, this study advances existing research by detecting the visibility of stroboscopic effects and systematically investigating visual responses in individuals with different visual conditions. These findings highlight the variability in visibility thresholds due to different experimental setups and conditions, emphasizing the importance of accounting for these factors when developing a comprehensive stroboscopic effect detection model for myopia individuals. Therefore, understanding these variations in visibility thresholds requires thoroughly considering the diverse measurement techniques and experimental parameters used across different studies.

5 Conclusion and Outlook

This paper reports the detection of stroboscopic effects in individuals with different visual conditions. The study indicates that the difference in visibility thresholds between wearing glasses and without is greatest at a 10% duty cycle, with this difference diminishing as the duty cycle increases. Future investigations should focus on developing a predictive model that incorporates myopia severity into the assessment of stroboscopic effect detection. Such a model would account for the varying degrees of myopia and provide a more tailored approach to predicting stroboscopic visibility thresholds based on individual myopic prescriptions.

Additionally, expanding the scope of research to include other significant factors is crucial. Future studies should explore the effects of stimulus shape, size, and luminance contrast on the perception of stroboscopic effects. These parameters may influence how stroboscopic effects are perceived and could further refine our understanding of the complex interplay between visual stimuli and stroboscopic visibility. Moreover, it would be beneficial to conduct research involving a broader participant base, including those with different visual conditions beyond myopia, to enhance the generalizability of the findings. Addressing these factors will contribute to developing comprehensive guidelines for designing visual displays and lighting systems that minimize stroboscopic effects and optimize visual comfort and safety for diverse populations.

Overall, advancing research in these areas will not only improve predictive models for stroboscopic effects but also provide deeper insights into the underlying mechanisms affecting visual perception in various conditions.

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