Influence of Temporal Frequency, Duty Ratio, and Eye-Stimulus Dynamics on Motion Artifacts

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Abstract

Motion artifacts—perceived discrepancies between displayed and natural images of motion stimuli—are influenced by display properties and their interaction with eye movements. Hoffman et al. (2014) proposed that a shorter duty ratio reduces motion artifacts when the eyes pursue a moving target. However, a recent study (Han et al., 2024) found that a longer duty ratio reduces motion artifacts when the eyes move while the stimulus remains static. This study examined the interactive effects of display temporal properties and eye-stimulus dynamics on motion artifacts. In Experiment 1, motion artifacts were measured across a wide range of refresh rates and duty ratios under two eye movement conditions. Results showed that higher temporal frequencies consistently reduced motion artifacts, while the effect of duty ratio depended on eye movement conditions. Experiment 2 investigated how speed differences between eye and stimulus movements influenced motion artifacts. Participants preferred a shorter duty ratio when eye and stimulus speeds were closely matched but favored a longer duty ratio in other cases. These findings provide reference data for practical applications, helping to predict motion artifact magnitude.

Author Keywords

Image Quality; Temporal Frequency; Eye Movement; Duty Ratio; Eye-Stimulus Dynamics; Motion Artifacts;

1. Introduction

The human visual system can process visual information within a limited range of spatiotemporal frequencies (Watson et al., 1986). These limitations have been leveraged to define display specifications. For example, a display's refresh rate is typically designed to reflect the critical flicker fusion frequency (CFF)—the minimum frequency required to prevent perceived flicker. However, CFF is based on a specific viewing condition in which the stimulus is stationary, and the observer's gaze is fixed, differing from natural viewing conditions where both stimuli and eyes are often in motion. When considering the dynamic movements of stimuli and the eyes, the duty ratio becomes another important factor influencing display quality. Duty ratio refers to the persistence of an image on a display during a single refresh cycle (Murdison et al., 2019). For instance, a 90% duty ratio at 100 Hz means the image persists for 9 milliseconds (ms) of a 10 ms refresh cycle.

Few studies have examined the effects of duty ratio on motion artifacts, which are perceived discrepancies between displayed and natural images of motion stimuli. Hoffman et al. (2014) asked participants to evaluate the quality of a displayed moving target while either tracking it with their eyes or fixating on a stationary cross. When tracking the moving target, participants perceived more blurred boundaries with a longer duty ratio than with a shorter duty ratio. However, when fixating on a stationary cross, duty ratio had no effect on motion artifacts. These findings demonstrate the interaction between duty ratio and eye movements in determining motion artifacts and support the claim that shorter duty ratios improve perceived image quality by reducing motion blur. In a subsequent study, Han et al. (2024) expanded on these findings by examining various eye movement scenarios. They investigated the effects of duty ratio on motion artifacts across different eye movement conditions: the eyes follow a moving object (Condition A), the eyes move while the stimulus remains stationary (Condition B), and the eyes perform saccadic movements to follow a moving object (Condition C). Participants reported whether a short (8%; 60 Hz) or long (92%; 60 Hz) duty ratio stimulus looked more similar to a reference stimulus presented at a high refresh rate (1440 Hz). The results revealed that in Condition A, consistent with a previous study (Hoffman et al., 2014), the shorter duty ratio appeared significantly more similar to the reference stimulus. However, in Conditions B and C, longer duty ratio stimuli were perceived as more similar to the reference stimulus. These findings indicate that the effects of duty ratio on motion artifacts depend on the specific eye movement scenario, challenging the notion that a shorter duty ratio results in better motion display quality.

In this study, we expanded previous research by quantifying the magnitude of motion artifacts which are affected by temporal frequency, duty ratio, and their interaction with eye movements. In Experiment 1. we quantified the effects of temporal characteristics on motion artifacts under Conditions A and B introduced above. Notably, we measured motion artifacts in wide range of refresh rates and duty ratios to provide a practically useful reference data set. The results demonstrated that motion artifacts decreased with increasing temporal frequency across both eye movement scenarios. However, an interaction was observed between duty ratio and eye movement scenarios: motion artifacts decreased with a shorter duty ratio in Condition A, whereas the opposite aspects were observed in Condition B, where longer duty ratios reduced motion artifacts. In Experiment 2, we examined the interaction between duty ratio and the speed difference between eye movements and the stimulus. The findings revealed that when the speed of eye movements closely matched the stimulus speed, a shorter duty ratio reduced motion artifacts. Conversely, a longer duty ratio reduced motion artifacts when the speed discrepancy was larger. These results indicate that motion artifacts are influenced by retinal signals that arise from interaction between eye movements and the persistence of images on the retina.

2. Method

Participants: Twelve subjects participated in Experiment 1 (6 male, including an author C.H., mean age 23.25 ± 3.33). In Experiment 1, six subjects participated in Condition A, which involved a moving stimulus with smooth pursuit, while the other six subjects participated in Condition B, which involved a stationary stimulus with smooth pursuit. Eight subjects participated in Experiment 2 (3 males, including an author C.H., mean age 22.89 ± 3.58). All participants had normal or corrected-to-normal eyesight. Except for the author, all participants were unaware of the experiment's goals. The study protocols were approved by Ulsan Institute of Science and Technology's Institutional Review Board (UNIST IRB).

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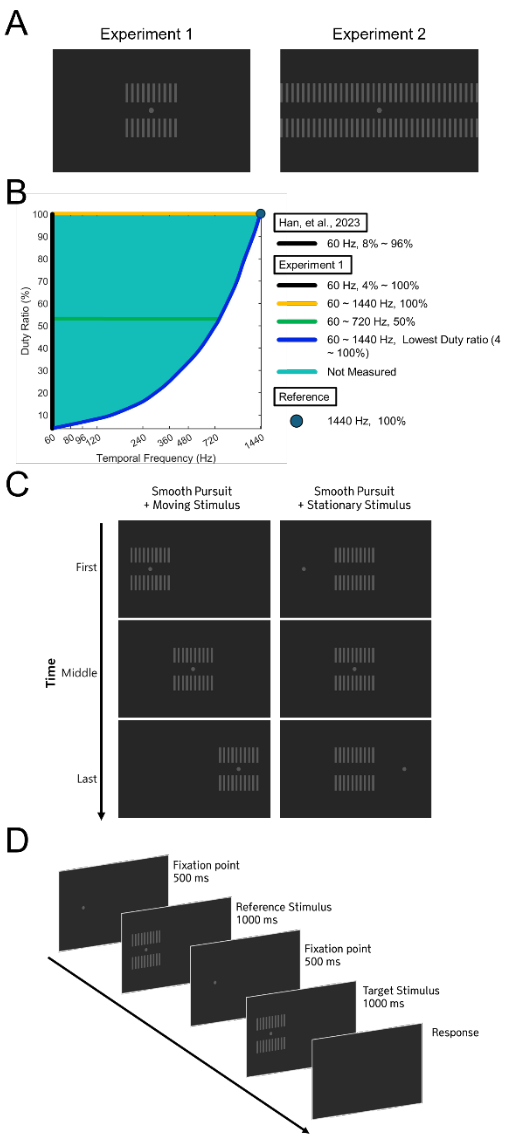

Figure.1. The method of Experiment 1-2. A, Stimuli for reference and target conditions. The left stimulus was used in Experiment 1, and the right in Experiment 2. B, Temporal frequency and duty ratio for the target stimuli in Experiment 1. The left graph illustrates the coverage of the projector, where the x-axis represents temporal frequency (Hz) and the y-axis represents duty ratio (%). The black line indicates the range of target stimuli from a previous study, while the yellow, green, and blue lines show the expanded range of target stimuli in this study. The cyan area indicates stimuli not measured due to display limitations. C, Conditions in Experiment 1. The left column represents Condition 1 (Smooth Pursuit + Moving Stimulus), and the right represents Condition 2 (Smooth Pursuit + Stationary Stimulus). Each row depicts frames at different times: the first, middle, and last frames. D, Experimental procedure. Participants compared target stimuli to the reference, identifying the most similar.

Apparatus: The participants sat in a dimly lit room. The chin rest with forehead stabilizer held the participant's head at 160cm from the projection screen. For showing stimuli at 1440 Hz, a PROPixx projector (VPixx Technologies, Saint-Bruno-de-Montarville, QC, Canada) was used. The experiment was written in MATLAB and presented using the Psychtoolbox (Brainard, 1997) and Eyelink toolboxes, and it was run on a MAC Pro (Apple, Cupertino, CA, USA). The left eye was monitored at 1000 Hz with an Eyelink 1000 Plus desktop mount (SR Research, Kanata, ON, Canada).

Stimulus:

Experiment 1: The stimulus consisted of ten vertical lines, each measuring 2 degrees of visual angle (DVA) in height and 0.1 DVA in width, as shown in Figure 1A. These lines were arranged horizontally with a spatial gap of 0.7 DVA. The eye movement conditions varied based on the movement of the stimulus and the fixation point (Figure 1C). The first condition is when both the stimulus and the fixation point moved linearly along the horizontal axis at a constant speed of 15 deg/sec (Condition A). The second condition is when the fixation point moved in the same manner as in Condition A, but the stimulus remained stationary (Condition B). Both fixation point and stimulus started with 7.5 deg left away from the center and ended at 7.5 right away from the center in Condition A. In Condition B, the fixation point moved the same way in Condition A, while the stimulus remained static in Condition B.

To compare the perception of the motion artifacts between the natural and limited temporal frequency of the movie, the stimulus was divided into two: The reference stimulus has the highest display refresh rate, 1440 Hz, and full duty ratio (100%). Another is the target stimulus, which has a lower temporal frequency than reference stimulus and varied duty ratio (Figure 1B). Due to limitations in display capabilities, specific combinations of temporal frequencies and duty ratios of target stimulus were selected to estimate motion artifacts efficiently. These combinations were adjusted based on each condition. In Condition A, duty ratios ranging from 4% to 100% in 4% increments were tested at 60 Hz. Additionally, the 100% duty ratio was tested at 60, 72, 80, 90, 120, 240, 720, and 1440 Hz, while 50% duty ratio was tested at 60, 72, 80, 90, 120, 240, and 720 Hz. The lowest available duty ratio was also tested at 60, 72, 120, 240, 720, and 1440 Hz. In Condition B, duty ratios from 4% to 100% in 4% increments were tested at 60 Hz, while 50% duty ratio was tested at 60, 72, 80, 90, 120, 240, and 720 Hz. The lowest available duty ratio was tested at 60, 72, 80, 90, 120, 240, 720, and 1440 Hz. The pair of target stimuli with adjacent variables were compared to reduce the overall experimental duration. All stimuli were displayed with equal mean luminance levels of 23 cd/m^2 to eliminate the effects of luminance modulation. The numbers of total trials were 1336 in condition A, 1200 in condition B.

Experiment 2: The stimulus consisted of numerous vertical lines (2 degrees of visual angle (deg) x 0.2 deg), filling the screen horizontally. These lines were arranged with a spatial gap of 0.8 deg between them (Fig 1A right). The reference stimulus was identical to that used in Experiment 1. The target stimulus was presented at a refresh rate of 60 Hz with duty ratio of either 8% or 100% to investigate the preference of a short duty ratio. All stimuli were displayed with an equal luminance of 47 cd/m^2 In Experiment 2, the independent variables were the speed of the stimulus and speed of the fixation point. The stimulus speed varied from 0 to 30 deg/sec in increments of 5 deg/sec, while the fixation point speed varied from 0 to 25 deg/sec in increments of 5 deg/sec.

Procedure: Participants were asked to select which target stimulus looked more similar to the reference stimulus (Figure 1D). In each trial, the fixation point of the reference stimulus was shown within 500 ms in advance, the reference stimulus was presented. The stimulus duration was fixed as 1 second. After reference stimulus was presented, the blank screen was shown in 1 sec, the fixation of the target stimulus was shown 500 ms in advance, the target stimulus was presented, and participant responded the answer. The reference stimuli above and below the fixation were the same, while the order of target stimuli was randomized by each trial. The fixation of the reference stimulus was the filled circle, and the fixation of the target stimulus was the open circle with 1 degree as diameter. After the response, the blank screen was shown within 1 second. All participants, including Experiment 1 and 2 practiced a few trials to understand the experimental procedure fully by conducting both conditions in Experiment 1. After the practice, participants conducted 80 trials in each condition. In addition, the block was divided into each condition, and the order of the blocks was randomized in each participant in Experiment 1. In each trial, the eye tracker recorded eye movement data to control the participants' eye movement. If the eye moved out of the range of the fixation (2 degree from the fixation point), they would receive the error message and repeat the trial.

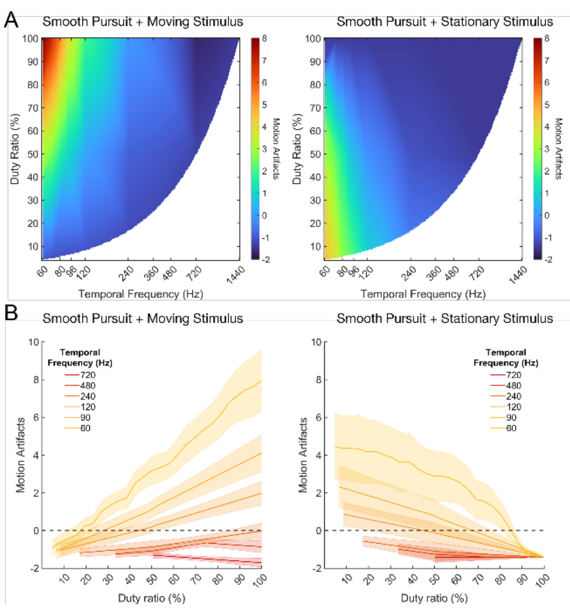

Figure.2. The results of Experiment 1. In graph A, the x-axis indicated the temporal frequency, the y-axis indicated the duty ratio, and the color of the area indicated the mean motion artifacts among the participants. As the color of the area is more reddish, the motion artifacts increased. The left graph is drawn when the participants' eye followed the moving stimulus, and right graph is drawn when the participants' eye moved while stimulus flickered in stationary. Graphs B were redrawn in terms of temporal frequency. The x-axis indicates duty ratio, and the y-axis indicates the motion artifacts. Each line indicated temporal frequency of target stimulus. The thin line indicated mean value among participants and the shade of each line indicates the error among the participants. When the line gets yellowish, the line indicates lower temporal frequency. The dotted line of each graph indicates that participants could discriminate the target stimulus from the reference stimulus with one standard deviation.

3. Results

To analyze the effect of duty ratio and temporal frequency within each condition, we employed the Thurstonian scaling to estimate the perceptual distance of the target stimulus from the reference stimulus, representing the level of motion artifacts. In other words, when the target stimulus appears more distinguishable from the reference stimulus, its motion artifacts are estimated to be higher. Within the Thurstonian scaling, we utilized the probability of participants selecting which target stimulus appeared more similar to the reference stimulus by using Monte-Carlo Markov Chain (MCMC) algorithm. The motion artifacts of the reference stimulus (1440 Hz and 100% duty ratio) were assumed to be zero, which was assumed to be a natural continuous motion (Watson et al., 1986). After Thurstonian scaling, we estimated the motion artifacts as a function of the experimental variables and subtract $\sqrt{2}$ as the one standard deviation. To estimate the full coverage of all possible variable combinations, we interpolated the motion artifacts obtained from the MCMC analysis.

In Condition A, Smooth Pursuit with Moving Stimulus, participants consistently perceived shorter duty ratios and higher temporal frequencies as more similar to the reference stimulus compared to longer duty ratios. As shown in Figure 2A left, the estimated motion artifacts, averaged across participants, decreased as the duty ratio decreased or the temporal frequency increased. These perceptual tendencies are further illustrated in Figure 2B left. At the highest temporal frequency (the most reddish line in Figure 2B), the motion artifacts were unaffected by changes in the duty ratio. In contrast, at lower temporal frequencies (the most yellowish line in Figure 2B), motion artifacts decreased with a reduction in duty ratio. In Condition B, Smooth Pursuit with a Stationary Stimulus, the results were notably different. Participants perceived longer duty ratios and higher temporal frequencies as more similar to the reference stimulus (Figure 2A right). However, in Figure 2B right, the trend flipped horizontally: at lower temporal frequencies, longer duty ratios resulted in fewer motion artifacts, while at higher temporal frequencies, the duty ratio had no discernible effect. Notably, the overall estimated motion artifacts in Condition B were significantly lower than those observed in Condition A.

In Experiment 2, we investigated the effects of the relative speeds of eye and stimulus movements on the perception of motion artifacts. This experiment was motivated by the findings from Experiment 1, which demonstrated that the effect of duty ratio on motion artifacts varied depending on the eye movement scenario. These differences suggested that the relative speed between eye and stimulus movements, independent of temporal frequency, modulates the perceptual impact of duty ratio. The speed of eye fixation ranged from 0 to 25 deg/sec, while the speed of stimulus movement varied from 0 to 30 deg/sec. Participants compared target stimuli with a temporal frequency of 60 Hz and duty ratios of 8% or 100%. When both the eye and stimulus were stationary (0 deg/sec), the probability of participants selecting the short duty ratio was assumed to be 0.5, indicating an inability to distinguish between the two target stimuli in terms of similarity to the reference stimulus. The average data across participants, shown in Figure 3A, was obtained through linear interpolation and smoothed using a 2d Gaussian filter, whose deviation is 1 deg/sec. The results revealed an interaction between eye-stimulus dynamics and duty ratio on motion artifacts. Specifically, most participants perceived the short duty ratio as producing fewer motion artifacts only when the speed of eye movement closely matched the speed of the stimulus, consistent with Hoffman's findings. However, in conditions where the speed of eye movement differed significantly from the speed of the stimulus, a longer duty ratio was preferred for reducing motion artifacts. This trend is further illustrated in Figure 3: individual participant data (Figure 3B) and the simplified summary graph (Figure 3C) highlight that the short duty ratio was perceived as more similar to the natural stimulus only in scenarios where the eye and stimulus movements were synchronized. In other scenarios, participants favored the longer duty ratio. Notably, in conditions where the eyes were stationary (fixation speed = 0), there was no preference for duty ratio, with a probability of 0.5 indicating indifference. At low fixation speeds (0 or 5 deg/sec), the interaction between duty ratio and motion artifacts diminished, converging the preference probability to 0.5. Additionally, Figure 3D demonstrates a significant linear correlation between the actual speed of eye movement and the fixation point speed among participants (Estimate = 1.136, Adjusted r^2= 0.9774)). This result confirms that the experiment effectively controlled participant eye movements and validates the observed interaction between eye-stimulus dynamics and duty ratio on motion artifacts.

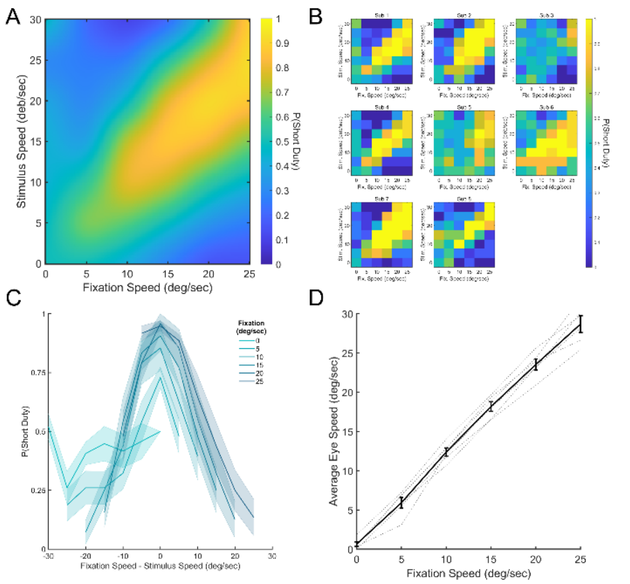

Figure.3. The results of Experiment 2. A, Average probability of selecting short duty ratio among subjects along with speed of fixation and objects. The x-axis is the speed of fixation, and the y-axis is the speed of the stimulus. The colormap indicates the probability of selecting the short duty ratio. The area is more yellowish, the short duty ratio looks like more reference stimulus. The probability was smoothened by 2d-Gaussian filter. B, the probability of selecting short duty ratio of each subject. C, the probability of selecting short duty ratio with difference of speed between fixation and stimulus. Each line indicates the speed of the fixation point. D, the relationship between the speed of eye movements and the speed of the fixation point. The x-axis is the speed of fixation points, and the y-axis is the speed of average eye movements. The dotted line indicates the relationship of each subject. The thick line indicates the mean relationship among subjects.

4. Discussion

Experiment 1 demonstrated that eye movements influence the interaction between duty ratio and temporal frequency. When the eyes tracked a moving stimulus, shorter duty ratios effectively reduced motion artifacts. Conversely, when the eyes moved while the stimulus remained static, longer duty ratios reduced motion artifacts. These effects of duty ratio were observed only at lower temporal frequencies, with no significant impact at higher temporal frequencies. This aligns with previous research on stroboscopic motion, which found that higher temporal frequencies reduce motion artifacts (Watson et al., 1986). Expanding on these findings, our study suggests that the effect of duty ratio may depend on temporal frequency, as higher temporal frequencies decrease image persistence, potentially diminishing the impact of duty ratio. Experiment 2 revealed that the speed difference between eye and stimulus movements determines the effect of the duty ratio. Specifically, shorter duty ratios reduced motion artifacts only when the speed of eye movements closely matched the speed of stimulus movements. In other scenarios, longer duty ratios were more effective at reducing motion artifacts. These results indicate that the preference for shorter duty ratios in reducing motion artifacts is relatively rare, compared to the more frequent preference for longer duty ratios. To optimize duty ratio for a given temporal frequency, statistical data on eye movements during natural movie viewing will be essential. Such data would enable the development of adaptive display settings that account for typical viewing conditions. Despite this limitation, the findings of this study provide foundational insights into the complex relationships between motion artifacts, duty ratio, temporal frequency, and the dynamics of eye and stimulus movements. These insights are critical for advancing display technologies and improving visual quality in diverse scenarios.

5. Conclusion

This study reveals the retinal signal which arises from the interplay between the relative speeds of eye and stimulus movements and persistence of image as duty ratio and temporal frequency in shaping motion artifacts. Experiment 1 demonstrated that higher temporal frequencies consistently reduce motion artifacts, while the effects of duty ratio are dependent on specific eye movement scenarios. Shorter duty ratios effectively reduced artifacts during tracking scenarios (Condition A), particularly at lower temporal frequencies, whereas longer duty ratios were effective in other scenarios (Condition B) at lower frequencies. Experiment 2 further demonstrated that the relative speed between eye and stimulus movements determines duty ratio preferences, with shorter duty ratios preferred only when their speeds closely match. Collectively, these findings emphasize that the optimal duty ratio is highly dependent on eye-stimulus dynamics, offering valuable insights for optimizing display performance in diverse viewing conditions.

6. Acknowledgements

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7. References

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