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Motion artifacts on 240-Hz OLED stereoscopic 3D displays

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Abstract— Temporal multiplexing is a popular approach for presenting different images to the two eyes in stereoscopic 3D (S3D) displays. We examined the visibility of flicker and motion artifacts—judder, motion blur, and edge banding—on a 240-Hz temporally multiplexed S3D OLED display. Traditionally, a frame rate of 120 Hz (60 Hz per eye) is used to avoid visible flicker, but there is evidence that higher frame rates provide visible benefits. In a series of psychophysical experiments, we measured the visibility of artifacts on the OLED display using temporal multiplexing and those of a 60-Hz S3D LCD using spatial multiplexing. We determined the relative contributions of the frame rate of the content, update rate of the display, duty cycle, and number of flashes. We found that short duty cycles and low flash numbers reduce the visibility of motion artifacts, while long duty cycles and high flash numbers reduce flicker visibility.

Keywords— *OLED, stereoscopic 3D, motion perception, frame rate, judder, flicker.*

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1 Introduction

A central pillar of display design is that motion looks smooth only if the display has a sufficiently high frame rate.¹ The majority of liquid-crystal displays (LCDs) and organic light-emitting diode displays (OLED) on the market utilize frame rates of 60 frames per second (Hz), producing little flicker and relatively smooth apparent motion. However, there is clear theoretical and empirical evidence that higher frame rates are needed to produce smooth motion for the gamut of typical object speeds.^{2–7}

Perceptual motion and flicker artifacts on display systems are influenced by the capture rate and presentation rate. *Capture rate* is the number of unique images presented per second and is primarily an attribute of the content. *Presentation rate* is the number of images presented on the screen per second, regardless of whether those images are unique or repeated (multi-flashed), and is limited by the display technology. Capture rate tends to be the primary factor determining the visibility of motion artifacts while presentation rate is the primary factor determining the visibility of flicker.⁶ Bex *et al.*⁴ showed that there is a fixed spatial displacement between image updates that acts as a threshold beyond which temporal aliasing occurs and that this coincides with the point at which motion-energy detection fails.⁸ Additionally, the duty cycle of the image presentation—the fraction of the presentation interval in which imagery is illuminated—affects the visibility of motion artifacts and flicker.^{3,6} We examined how capture rate, presentation rate, and duty cycle affect the visibility of motion artifacts and flicker on a 240Hz OLED panel.

Figure 1 summarizes how particular driving modes and viewing conditions stimulate the retina leading to different types of motion artifacts. Consider a viewer fixating on a stationary point on the screen while an object moves past. Because movement on the display is quantized, the object jumps across the retina in discrete steps (Fig. 1, left column). The displacement of each jump on the retina is the object speed divided by the capture rate of the content. If the displacement is too large, motion appears unsmooth. The unsmooth appearance is called *judder*. Duty cycle (panels A and B) as well as multiple-flash presentation (panel C) does not impact the spatial position of the retinal image during fixation. Now consider the situation in which the viewer tracks a moving object by making a smooth-pursuit eye movement. With real objects, such tracking stabilizes the object's image on the retina. With digitally displayed objects, the tracking has a different effect, as illustrated in the right column of Fig. 1. The eye movement causes the discrete image to smear across the retina for the duration of the presentation interval; this is perceived as *motion blur*.² The magnitude of the blur is proportional to the duration of each image presentation and thus motion blur should be greater with longer duty cycles (panel B vs. panel A). Cathode-ray-tube (CRT) displays have an impulse-like temporal response, similar to panel A in Fig. 1, which keeps motion blur to a minimum. Liquid-crystal displays (LCDs) as well as OLEDs have a sample-and-hold temporal response, similar to panel B in Fig. 1, suggesting that motion blur could be more prominent in these displays. In cases of multi-flash presentations, another effect—*edge banding*—can occur (Fig. 1, panel C) in which repeated presentation of an edge creates the appearance of ghost edges.

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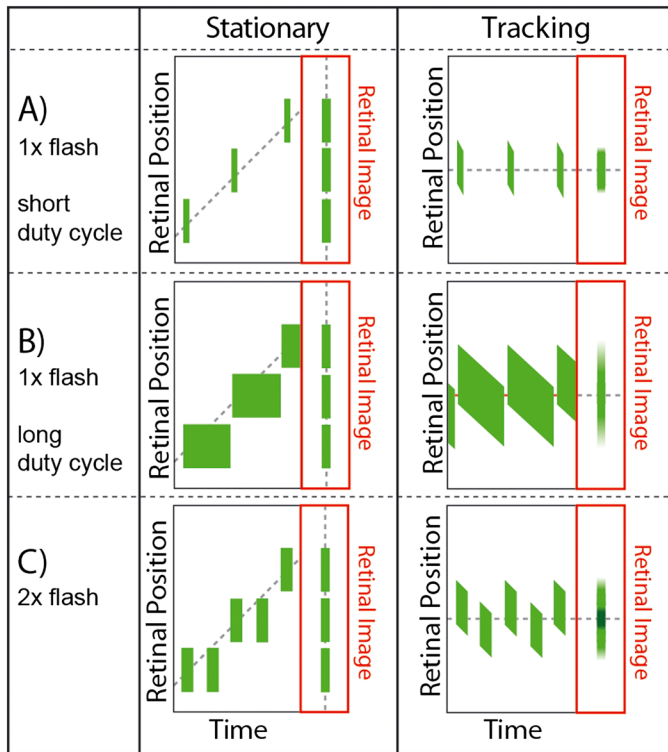


FIGURE 1 — Retinal-image stimulation with different display protocols, with stationary fixation and eye tracking. The left sub-region of each panel shows a time and position plot, and the right region shows a cross section of the retinal image integrated over time. The left panels show the motion along the retina over time when fixation is stationary. The right panels show the retinal motion when the object is tracked with a smooth-pursuit eye movement. A). Single flash (1 \times), short duty cycle (as in a stroboscopic display). B). Single flash, long duty cycle ~ 1.0 (as in a sample-and-hold display). C). Double flash (2 \times), duty cycle ~ 0.5 (similar to temporally multiplexed S3D display).

Motion artifacts are a spatiotemporal phenomenon involving position and time whereas flicker is purely a temporal artifact. Flicker refers to the sensation of brightness instability. When the duty cycle of a display is less than 1.0, the luminance of a scene shown by the display changes over time. This change becomes visible when the presentation rate is below the *critical flicker fusion frequency*, which limits the maximum perceptible frequency of luminance change.

The concept of the *window of visibility* was first proposed by Watson *et al.* and is a simplified band-pass illustration of the visual system and stimulation in Fourier space.³ It can be used to make predictions of the visibility of different motion artifacts and flicker. Consider an object moving across the screen at speed s in Fig. 2. The gray diagonal lines in the left panels represent continuous motion and the blue dots represent stroboscopic sampling of this motion. The Fourier transform of the smoothly moving stimulus is the gray line in the right panels, which has slope $-1/s$. Sampling the continuous motion creates replicates: the blue lines. The overall spectrum contains a signal component as well as the replicates. These replicates are only visible if they appear within the window of visibility (schematized by the dashed diamonds in the right panels). This is the region in Fourier space

corresponding to the range of spatial and temporal frequencies to which the human visual system is sensitive.³ The vertex of the window on the temporal-frequency axis represents the critical flicker fusion frequency, or the temporal frequency above which flicker cannot be perceived. Below the critical flicker fusion frequency, flicker visibility will depend on the contrast of the stimulus, with higher contrast stimuli having more visible flicker.² The vertex of the window on the spatial-frequency axis represents the visual-acuity limit, or the highest spatial frequency that is visible. If aliases are present within the window of visibility, motion artifacts may be visible. The horizontal distance between aliases in Fourier space is equal to $1/\Delta t$, where Δt is the rate at which content is captured, suggesting that a higher capture rate would spread aliases further apart, which would make them less likely to infringe on the window of visibility. A capture rate of 60 Hz (Fig. 2, top panels) could cause motion artifacts at this particular object speed, while a capture rate of 120 Hz (Fig. 2, bottom panels) would not. Additionally, the slope of the aliases is the negative reciprocal of speed, so even a capture rate of 120 Hz would not prevent motion artifacts at sufficiently high speeds. It should, however, allow for a greater range of speeds that are free of artifacts. Note that if the eyes are tracking the stimulus, we can plot the retinal position over time as a horizontal line, which would make the signal (and aliases) vertical lines in frequency space. These spatiotemporal aliases would create a different motion artifact percept than in the stationary case.⁶

In stereoscopic 3D (S3D) displays, the method used to send left- and right-eye images to the appropriate eye can influence the visibility of artifacts. Temporally multiplexed displays present left- and right-eye images alternately in time. Such multiplexing has a maximum duty cycle of 0.5 because each eye only receives an image at most half of the time. In reality, the duty cycle is usually less than 0.5. Liquid-crystal shutter glasses, which are often used to block left- and right-eye images, have some switching time and therefore lead to an inherent tradeoff between maximizing duty cycle and minimizing crosstalk, which is the bleeding of one eye's image into the other eye. We investigated duty cycles of 0.5 and less using an OLED display. To investigate a duty cycle of 1.0, we employed a spatially multiplexed display. Spatially multiplexed displays use a film-patterned retarder to present the left-eye image on even (or odd) rows and the right-eye image on odd (or even) rows. In this method, the two eyes are stimulated simultaneously, so one can generate a duty cycle of nearly 1.0. Thus, when tracking an object, motion blur should be more visible on a spatially multiplexed display than on a temporally multiplexed display.

Unlike LCDs, which have response times on the order of 4–9 ms,⁹ OLED displays have a temporal response of less than 300 μ s in typical cases because they are limited only by the driving electronics.¹⁰ OLED displays can thus be driven at high frame rates. A particular 240-Hz OLED display prototype is capable of showing 240 unique frames per second and thus supports faster-than-normal capture rates and could

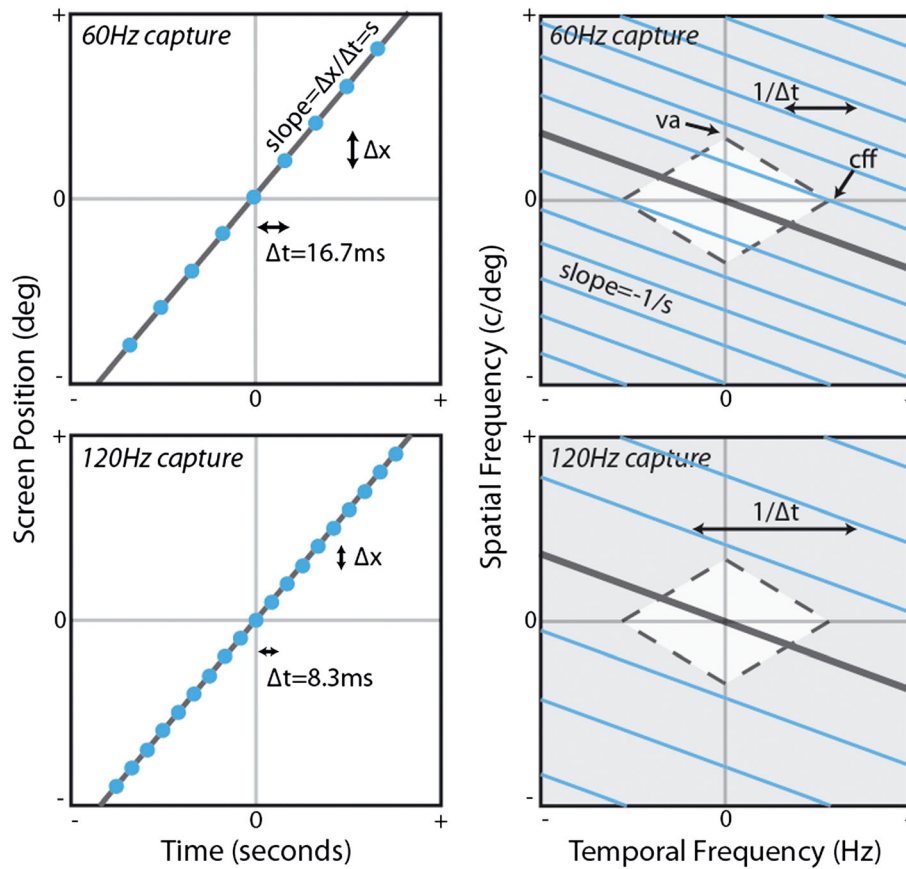


FIGURE 2 — Effect of stroboscopic sampling on amplitude spectrum. The gray diagonal lines in the left panels represent smooth motion, and the blue dots represent stroboscopic sampling at two different intervals: 60 Hz (top) and 120 Hz (bottom). The right panels show the resulting amplitude spectra of the continuous signal (gray line) as well as replicates caused by sampling (blue lines). The diamond represents the window of visibility, the range of spatial and temporal frequencies that is visible. The critical flicker frequency (cff) is the highest visible temporal frequency and the visual-acuity limit (va) is the highest visible spatial frequency. Replicates that fall within the window of visibility can cause motion artifacts, while replicates that remain outside the window are invisible.

thereby greatly reduce motion artifacts.¹¹ The high frame rate also enables a dual-viewer S3D mode in which the four views needed for two viewers to see a left- and right-image pair are temporally multiplexed on a single display. Two possible driving modes are $L_A R_A L_B R_B$ and $L_A L_B R_A R_B$, where L_A and R_A are the left- and right-eye views for viewer A, and L_B and R_B are the left- and right-eye views for viewer B. We will refer to these protocols as LRXX and LXXR, respectively. The delay between the left- and right-eye views, or the interocular delay, is different in these two driving modes; LRXX has an interocular delay of $1/240$ s while LXXR has an interocular delay of $1/120$ s. Techniques have been proposed to predict and measure motion blur using digital measurement devices,^{12–15} and to create industry standards for the measurement of motion artifacts,¹⁶ but to the best of our knowledge there is no metric that can accurately predict the severity of multiple types of motion artifacts.

We used a series of psychophysical experiments to measure the visibility of motion artifacts. Many of the effects we observed are consistent with an analysis of spatiotemporal signals in the frequency domain.^{3,6,8}

2 Experiment 1: motion artifacts

2.1 Methods

To present S3D images, we used a prototype Samsung 240-Hz OLED display that employs temporal multiplexing and a commercially available LCD display (LG 47LM4700) that employs spatial multiplexing. The diagonal lengths of the active areas of the OLED and LCD displays were 55 in (1.40 m) and 47 in (1.19 m) respectively. Viewing distance was 3.18 times picture height such that one pixel subtended 1 arcmin, or 2.18 meters for the OLED display and 1.86 meters for the LCD display. Five subjects took part in the experiments. All had normal or corrected-to-normal vision. They wore the appropriate stereoscopic glasses for each display. On the temporally multiplexed OLED, active shutter glasses were used, operating in one of two custom modes: left–right–left–right or left–left–right–right. On the spatially multiplexed LCD, passive polarized glasses were used. The measurements were done both with stationary fixation and with tracking eye movements. For the LCD and OLED displays, we tested a range of

capture and presentation protocols. In all, there were 18 conditions (nine presentation protocols with two eye-movement instructions). Figure 3 shows all the driving modes we tested. We presented 40 trials for each condition and speed, using the method of constant stimuli. For each type of stimulus, we asked the observer to report whether he or she perceived any motion artifacts, and we calculated the fraction of the 40 trials in which motion artifacts were reported. We fitted a cumulative Gaussian to the psychometric data using a maximum-likelihood criterion^{17–19} and extracted the object speed at which observers perceived motion artifacts half the time.

Figure 4 depicts the moving stimuli and fixation targets. In the tracking condition, the fixation target was initially off to one side, so the upcoming eye movement had to cross screen center. In the stationary condition, the fixation target was at screen center. The stimulus—a group of white squares moving horizontally at a constant speed—was visible for 1 s. Following the presentation, subjects reported whether or not they saw motion artifacts in the moving squares. Subjects were directed to respond regardless of the type of motion artifact perceived (i.e. blur, edge banding, or judder). It was often hard to articulate which type of motion artifact was present because they all can be present at once. Thus we focused on visibility of any motion artifact, rather than differentiating the types of artifacts.

2.2 Results

Figure 5 shows the effect of capture rate on artifact visibility on the OLED display for all five observers. Each panel plots for a different subject the object speed at which artifacts were visible as a function of capture rate. Thresholds generally increased with capture rate up to the maximum rate of 120 Hz. There is noticeable inter-subject variability in the stationary condition at high capture rates, but observers were

fairly consistent in their own artifact ratings. For simplicity in subsequent plots, thresholds are averaged across subjects and the error bars represent the standard deviation for the observers.

One of our core experimental questions concerned the difference between the presentation rate and capture rate. We examined how (single, double, and quadruple) flashing affects the visibility of motion artifacts in order to evaluate the assertion that strobed presentation can improve the quality of perceived motion. Figure 6 shows data pooled across subjects, for the stationary and tracking conditions, and demonstrates the relationship between the number of flashes and motion artifacts. There was a clear effect of capture rate on artifact visibility in both the stationary and tracking cases. At the lowest capture rate of 30 Hz, we tested the double- and quadruple-flash protocols only because single flash had unacceptable flicker. There was no significant difference between double and quadruple flash with 30-Hz capture. At 60-Hz capture, we could only test single- and double-flash protocols. There was no significant benefit of single flash over double flash in the stationary condition, but in the tracking condition, motion was significantly smoother with single flash than double flash (paired *t*-test, $p < 0.01$). These results—no difference during stationary fixation and large differences during tracking—are consistent with the predictions of the retinal-position model in Fig. 1. In other words, artifacts in the stationary condition were more likely caused by judder, while artifacts in the tracking condition were more likely caused by motion blur or edge banding.

We can also carry out a similar analysis to assess impact of the duty cycle of the presentation. Figure 7 shows the results for duty cycles of ~ 0.25 , ~ 0.5 , and ~ 1.0 with a capture rate of 60 Hz. A spatially multiplexed display was used for the duty cycle of 1.0. In the stationary condition, duty cycle had no significant effect on motion artifacts. In the tracking condition,

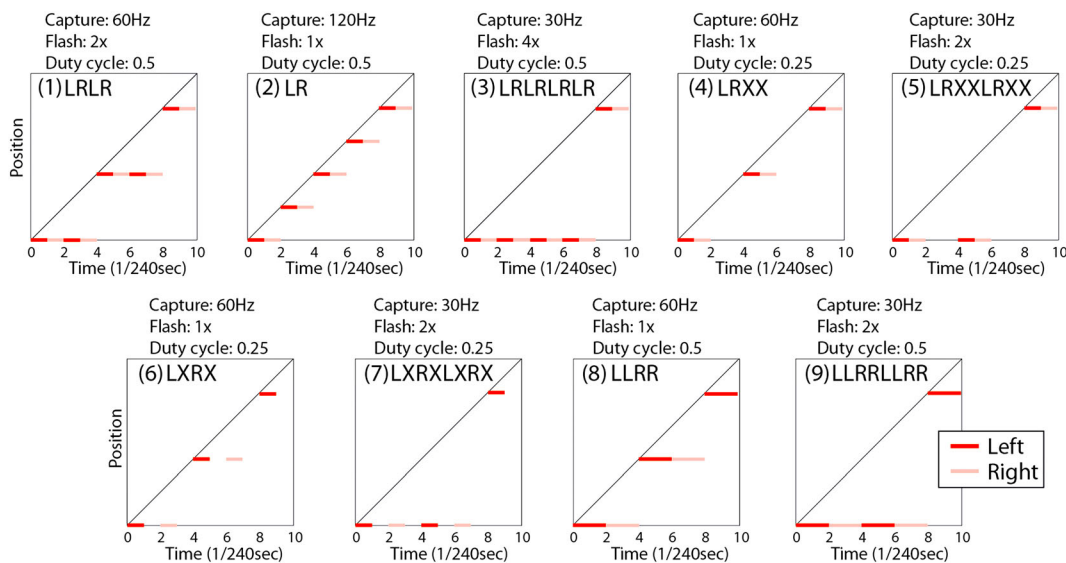


FIGURE 3 — Driving modes presented on the 240-Hz display with associated capture rate, flash number, and duty cycle. The gray diagonal line represents smooth continuous motion, and the horizontal red and tan lines represent left- and right-eye views, respectively.

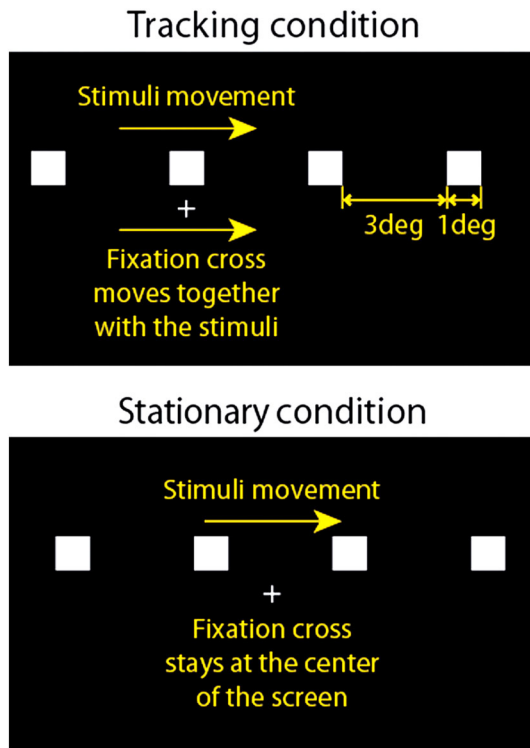


FIGURE 4 — Stimulus and fixation target in the tracking and stationary conditions. A trial consisted of three parts: initial fixation, stimulus motion, and response collection. In the tracking condition, the fixation target moved with the same velocity as the squares across the center of the display. In the stationary condition, the fixation target remained stationary.

there was a clear effect of duty cycle: The ~ 1.0 duty cycle caused motion artifacts at approximately half the speed of the ~ 0.5 duty cycle presentation. The shortest duty cycle of ~ 0.25 supported the fastest motion without artifacts. This effect in the tracking condition was due to the increase in motion blur with larger duty cycles.

We measured the effect of interocular delay on the visibility of motion artifacts by comparing the LRXX and LXX protocols. Figure 8 shows the results. There was no systematic effect of interocular delay on motion artifact visibility. This finding is consistent with the experiments by Hoffman *et al.*⁶ who concluded that the visibility of motion artifacts is determined by monocular signals. Interocular delays have an

influence, however, on other effects such as depth distortion and flicker.^{6,11}

3 Experiment 2: flicker

Although presentation rate is an important determinant of flicker visibility,⁶ other factors—e.g. luminance, contrast, temporal vs. spatial multiplexing, duty cycle—contribute as well. Flicker visibility is well predicted by the amplitude and frequency of the Fourier fundamental of the luminance-varying monocular signal from a display. Temporally multiplexed S3D displays require duty cycles of 0.5 or less, which increases the amplitude of the fundamental frequency compared to the larger duty cycle on spatially multiplexed displays.²⁰ Further reductions in duty cycle in temporally multiplexed displays, such as occurs in dual-viewer mode, decrease duty cycle yet further and this too causes an increase in the amplitude of the fundamental.²⁰ One therefore expects more visible flicker with temporally multiplexed displays compared to spatially multiplexed displays and more visible flicker in dual-view as opposed to single-view mode. Furthermore, a presentation rate of 60 Hz may be inadequate to completely avoid flicker for certain driving modes. There are areas of the peripheral visual field with flicker fusion frequencies as high as 85 Hz, while the fovea is ~ 55 Hz.²¹ This suggests that 60 Hz may be sufficiently fast for foveal targets but not for areas in peripheral vision.

3.1 Methods

To measure flicker thresholds on the OLED display, we used the same setup as in Experiment 1. Four subjects with normal or corrected-to-normal vision took part in the experiment. The visual system is somewhat more sensitive to flicker in the peripheral than in the central visual field.²¹ For this reason, we presented stimuli in the periphery in this experiment in order to obtain a worst-case estimate of flicker visibility. Subjects viewed the display from half the normal viewing distance and fixated on a cross 20 arcmin from the top of the screen. A solid gray rectangle was presented for 1 s in the

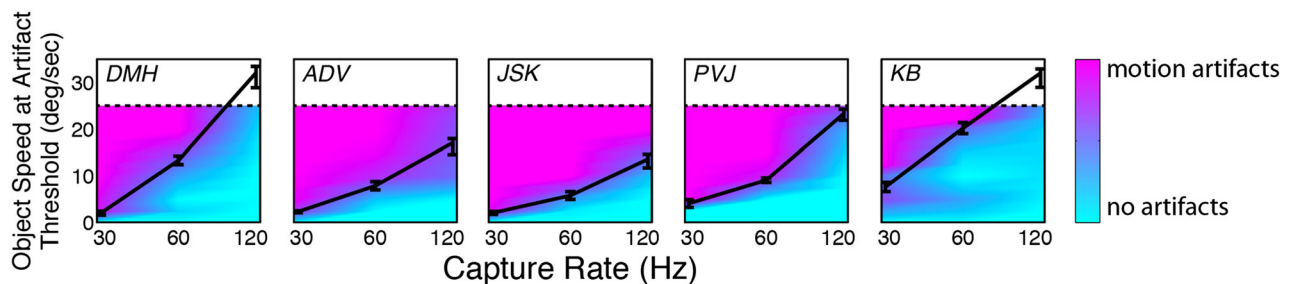


FIGURE 5 — Variation between observers and effect of capture rate on motion artifacts for the stationary fixation condition. Object speed at which artifacts were reported on half the trials is plotted as a function of capture rate. Thus, greater ordinate values indicate fewer motion artifacts. Each panel shows the data from one subject. Interocular delay was 1/240 s. Presentation was single flash except for the 30-Hz capture rate, which was double flash. Protocols correspond to #2, 4, and 5 in Fig. 3. Error bars represent 95% confidence intervals. The fastest speed tested was 25 deg/s (dashed line), so any thresholds above that value are an extrapolation. DMH, ADV, JSK, and PVJ were authors; KB was not.

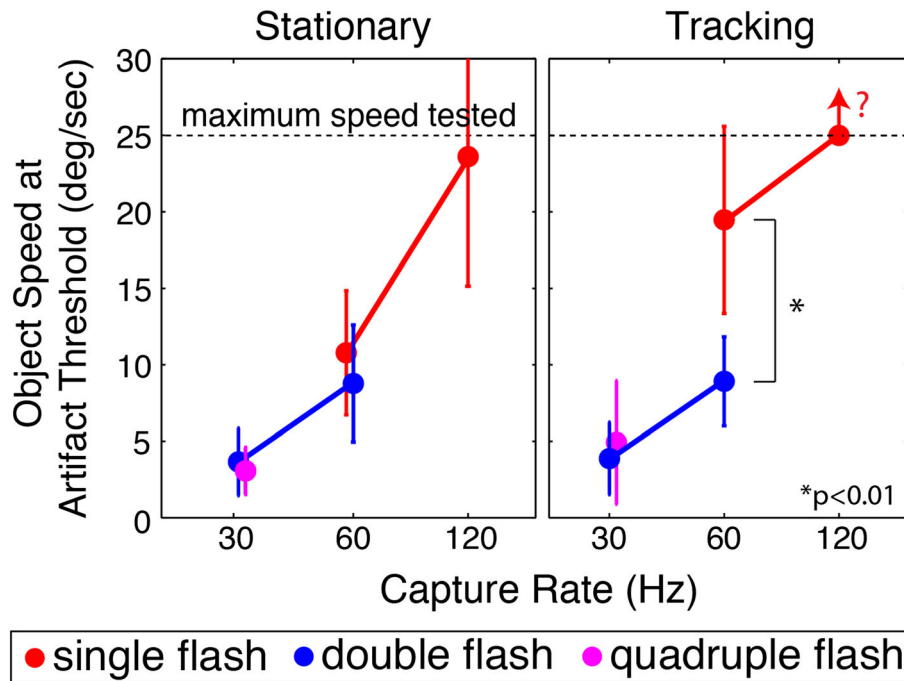


FIGURE 6 — Effect of flash number on motion artifacts. The data have been averaged across the five subjects. The object speed at which artifacts occurred half the time is plotted as a function of capture rate. The left and right panels correspond to stationary and tracking conditions, respectively. The dashed horizontal line represents the maximum speed tested. Thresholds that lie on that line indicate that no motion artifacts were observed at the fastest speed tested; extrapolating the exact threshold in those cases would be unjustified. Error bars indicate one standard deviation from the mean. The protocols tested correspond to protocols #1, 2, 3, 8, and 9 in Fig. 3. All protocols have duty cycle 0.5. The comparison marked with a bracket indicates a significant difference as evidenced by a paired *t*-test ($p < 0.01$).

lower center of the screen, subtending an angle on the retina of 20° (horizontal) by 13.3° (vertical). In retinal coordinates, the stimulus was located between 22.7° and 35.7° in the peripheral visual field, which is approximately where Tyler²¹ found the highest flicker fusion frequencies. Subjects indicated whether the rectangle appeared to flicker. We presented stimuli with different luminance values using a staircase to determine the point at which subjects perceived flicker half the time. All single- and dual-view modes were tested.

3.2 Results

We measured the visibility of flicker for the different driving modes. Figure 9 shows flicker thresholds as a function of display protocol. Thresholds represent the luminance above which a large bright object in the peripheral vision appeared to flicker. There was a small decrease in flicker visibility when the left- and right-eye images were 180° out of phase (LXX) as opposed to 90° out of phase (LRXX). A long duty cycle (LLRR) decreased flicker visibility further. A double flash protocol (LRLR) had no visible flicker whatsoever, even when the display was at maximum screen brightness. In this case, the 120-Hz fundamental frame rate per eye is well above the critical flicker frequency of the visual system, even in

peripheral areas of the visual field. The spatially multiplexed display had no visible flicker (data not shown).

4 Discussion

We have shown that higher capture rates yield fewer motion artifacts, but that capture rate is not the only predictor of such artifacts. We also showed that a longer duty cycle yields more motion blur if the viewer is tracking a moving object, but fewer artifacts than in the stationary case, even for a duty cycle near 1.0. Generally, subjects were more sensitive to motion artifacts in the stationary condition than the tracking condition. In typical cases, viewers will most likely track salient objects in the scene and therefore be substantially less likely to attend to objects outside of fixation that may suffer from judder.

To explain why judder is worse during stationary fixation compared to tracking, consider the signal in Fourier space when the viewer tracks a moving object. When we plot the *retinal* position of a moving object as a function of time, as in Fig. 10, the object moves across the retina in the stationary condition, but remains still in the tracking condition. If the slope of the continuously moving object is s , then the slope of the signal and replicates in Fourier space

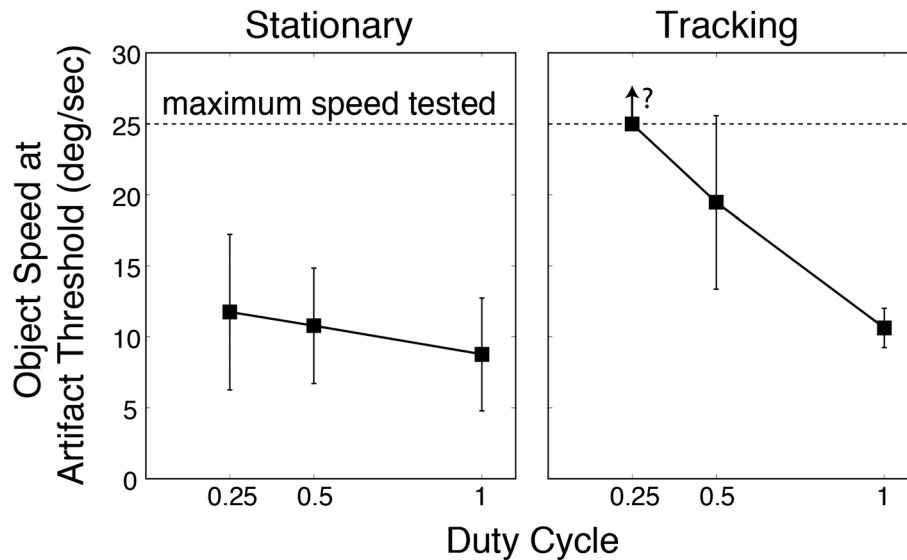


FIGURE 7 — Effect of duty cycle on motion artifacts. The left panel corresponds to the stationary condition and the right panel to tracking. The object speed at which artifacts were reported on half the trials is plotted as a function of duty cycle. The capture rate was 60 Hz and presentation was single flash. Duty cycles of 0.25 and 0.5 were presented on the temporally multiplex display, and the duty cycle of 1.0 on the spatially multiplexed display. We excluded one subject's data in the right panel because we could not fit the psychometric function to some conditions. Error bars represent one standard deviation. Some error bars are too small to see in this plot. The temporal multiplexing protocols tested correspond to protocols #6 and #8 in Fig. 3.

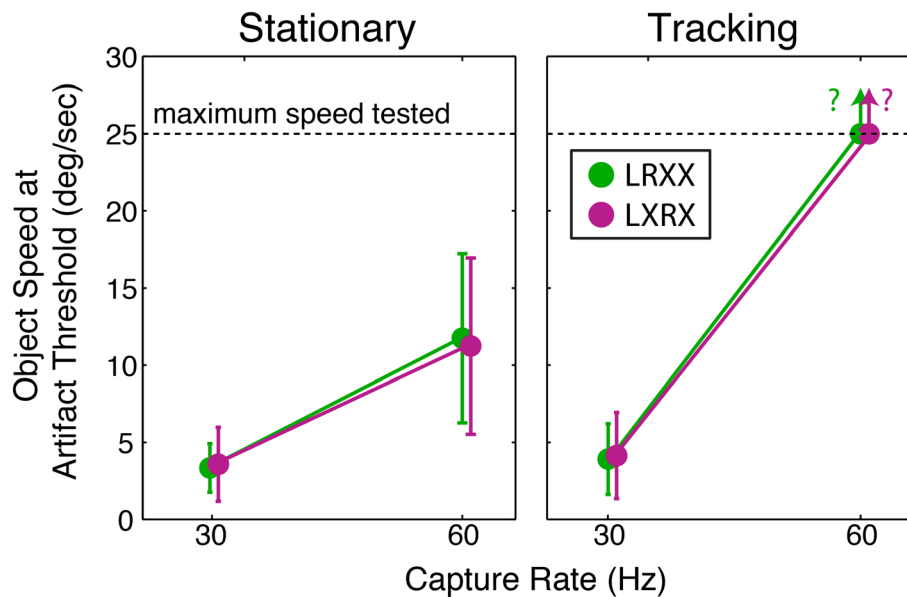


FIGURE 8 — Effect of interocular delay on motion artifacts. The slowest object speed at which artifacts were reported on half the trials is plotted as a function of capture rate, for stationary (left) and tracking (right) conditions. Green and magenta circles correspond to LRXX and LXX protocols, respectively (protocols #4–7 in Fig. 3). Error bars represent one standard deviation.

is $-1/s$. The slope influences how much of the replicate energy falls within the window of visibility in the stationary condition. As the speed of the object increases, the replicates tip further and intrude deeper into the window of visibility, causing more severe judder. In the tracking condition, replicates are sheared such that they become vertical (assuming perfect tracking), which has the same effect as slowing down the stimulus. This reduces the extent to

which replicates fall within the window of visibility and therefore reduces judder.

Motion blur, on the other hand, is due to the sample-and-hold property of OLED and LCD displays. The retinal-position hypothesis provides one explanation for why a longer duty cycle increases motion blur, but an analysis of signals in Fourier space can provide insight into why this happens. A sample-and-hold protocol with a duty cycle of

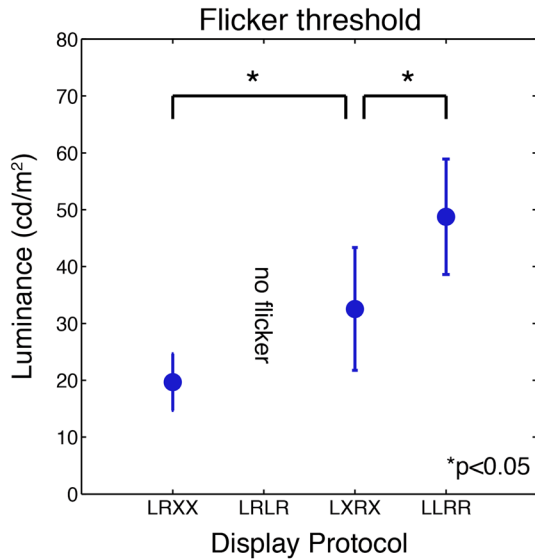


FIGURE 9 — Flicker thresholds averaged across the subjects. Thresholds signify the luminance value above which flicker is perceived for a large bright object in the peripheral visual field. Comparisons marked with the brackets at the top indicate significant differences as evidenced by a paired *t*-test ($p < 0.05$). Error bars represent one standard deviation.

0.5 is used to present the motion schematized in Fig. 10. We can think of a sample-and-hold protocol as stroboscopic sampling convolved with a *rect* function. In frequency space, that has the effect of multiplying by a *sinc* function. The sharpness of an object is determined by high-spatial-frequency information near a temporal frequency of 0. In the stationary case, the *sinc* function is oriented vertically with a peak-to-trough distance of $1/(d\Delta t)$ in the horizontal (temporal frequency) direction, where d is the duty cycle and Δt is the capture period. The *sinc* envelope has no effect on high spatial frequencies when the temporal frequency is low, so duty cycle does not create motion blur in the stationary case. In the tracking case, however, the *sinc* function is sheared vertically, which has the effect of attenuating high spatial frequencies at a temporal frequency of 0, causing motion blur. Furthermore, the spread of the *sinc* function in frequency space is a function of the duty cycle as well as speed of the object; the peak-to-trough distance is $1/(ds\Delta t)$ in the vertical (spatial frequency) direction, and remains $1/(d\Delta t)$ in the horizontal direction. In Fig. 10 the duty cycle is 0.5, which would produce a vertical spread of $2/(s\Delta t)$. With a lower duty cycle of 0.25, this distance would be $4/(s\Delta t)$, spreading the *sinc* further in the vertical direction, reducing the attenuation of high spatial frequencies within the window of visibility. This would make blur due to motion less apparent. The width of motion blur can also be expressed in units of retinal distance rather than frequency units. In this case, the width of the blur, b , can be expressed using the following equation:

$$b = \frac{f - 1 + d}{f} s\Delta t \quad (1)$$

where f is the number of flashes, d is duty cycle, s is object speed, and Δt is capture period. Note that for multiple flashes, the blur width is confounded by the fact that other artifacts such as edge banding may be visible, but this equation provides an upper limit for the retinal blur that can occur.

It is important to consider the normal range of object speeds in typical content. A study of Japanese households and broadcast content estimated the viewing conditions and content that people typically experience in their homes.²² Based on knowledge of how far people sit from their TVs and the motion in broadcast content, they found speeds of less than 10 deg/s in 40% of scenes, 10–20 deg/s in 30% of scenes, and 20–40 deg/s in 30% of scenes. This finding, combined with our result that motion artifacts are generally visible in the range of 10–20 deg/s when the capture rate is 60 Hz, suggests that a capture rate of 60 Hz is inadequate to create smooth motion in typical scenes. Particularly when viewers are fixating on a static part of the scene, they are likely to experience significant artifacts.

Presentation rates of 60 Hz per eye or higher are used in displays to avoid visible flicker on moderately bright displays. Sample-and-hold displays, including OLEDs and LCDs, do not have such a strict requirement because the long duty cycle has the effect of attenuating spatiotemporal aliases in the frequency domain. Regardless, these displays are traditionally driven at 60 Hz per eye or higher to create reasonably smooth motion. However, temporal multiplexing for S3D lowers the duty cycle and makes flicker an important consideration. Frame rates must therefore be higher than an equivalent non-stereoscopic display. Our results demonstrate that 60-Hz presentation is inadequate to completely eliminate flicker in peripheral vision for any of the dual-viewer modes. However, the 240-Hz OLED display has a high enough frame rate to afford some flexibility in how stereoscopic 60-Hz content is presented in single-viewer mode. If eliminating flicker is a priority, then content could be presented with double flash (LRLR). If eliminating motion artifacts is a priority, content could be presented with single flash and the lowest possible duty cycle of ~ 0.25 (LXRX or LRXX) to reduce blur. In this case, flicker could be noticeable in certain types of content, particularly when there are large areas of high luminance.

Multiple-flash protocols, while helpful for minimizing flicker, can cause artifacts of their own. In digital 3D cinema, the popular RealD format presents 24-Hz content using a triple-flash display protocol for a presentation rate of 72 Hz. This triple-flash technique ensures that the presentation rate is high enough to avoid visible flicker. In S3D cinema, left- and right-eye views are interleaved temporally for a presentation rate of 72 Hz per eye or 144 Hz overall. This driving scheme produces obvious motion artifacts, predominantly edge banding. However, attempts to move to higher capture rates—such as in Peter Jackson’s *The Hobbit*, filmed (capture rate) at 48fps—have received mixed feedback. Many viewers complain of a so-called “soap opera” effect that causes content to feel less cinematic, like a made-for-TV movie.²³ To the best

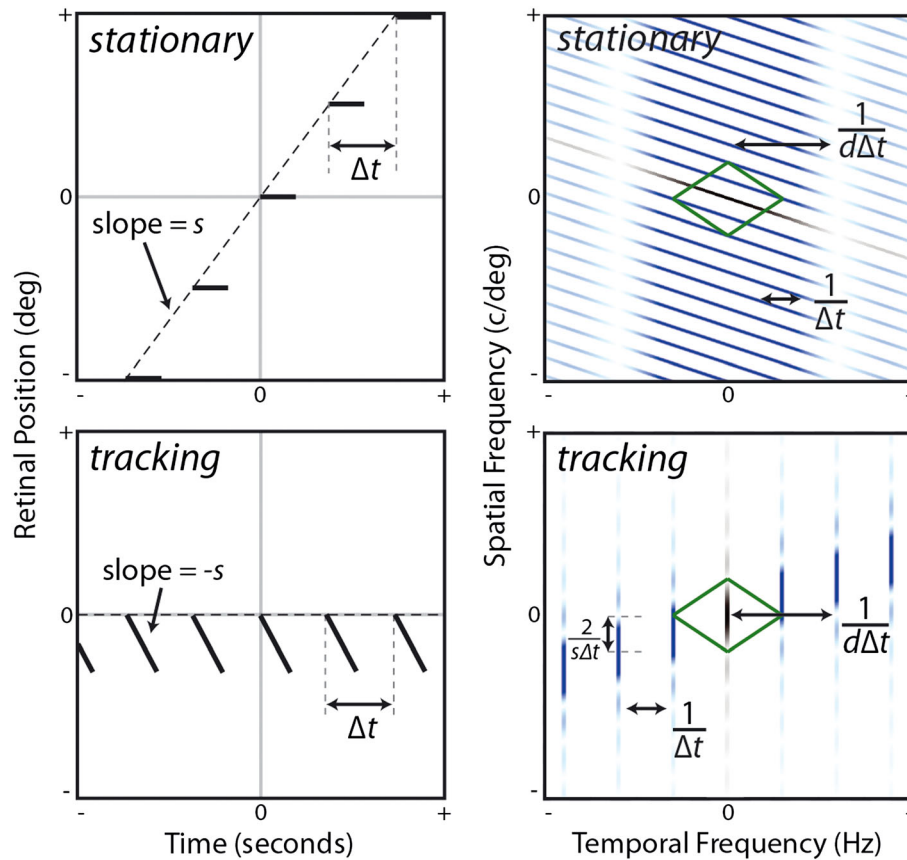


FIGURE 10 — Effect of eye movements on the perception of judder and blur. The top panels correspond to the stationary fixation condition and the bottom panels to the tracking condition. The black lines in the left panels show the retinal position over time of a smoothly moving object presented using a sample-and-hold display. The right panels show the resulting amplitude spectra of the continuous signal (black) and replicates (blue). The diamond represents the window of visibility. In the stationary condition, replicates are located within the window of visibility, causing judder. In the tracking condition, replicates remain outside the window of visibility, but high-spatial-frequency information in the signal has been lost due to sample-and-hold presentation.

of our knowledge, this effect has not been rigorously characterized. An important consideration could also be the shutter function used to capture content. For a capture rate of 24 Hz used in cinema, the shutter is kept open for a long time to increase motion blur, which makes motion appear smoother for content that would otherwise suffer from extreme judder.⁶ Computer games are typically rendered without motion blur and thus have many sharp moving edges that are prone to judder. Reconsidering the shutter function for high capture rates could provide benefits. If the shutter function in the filming of *The Hobbit* was the same proportion of the frame capture period, its duration would have been half the duration of standard 24-Hz capture, thereby decreasing motion blur and increasing judder.

These experiments have shown some large differences in how motion artifacts are perceived depending on eye movements, capture rate, and duty cycle. The dual-viewer modes supported by the 240-Hz OLED display are effective at producing fewer motion artifacts than spatially multiplexed displays largely due to differences in the duty cycle, even though they are slightly more susceptible to visible flicker

than either of the single-viewer modes. It is also worth considering that the spatially multiplexed display used in this study is an LCD, not an OLED. Compared to OLED displays, LCDs have slower, and asymmetric, rise and fall times and are therefore less temporally precise.²⁴ LCD response times can even exceed one frame.²⁵ This could result in greater amounts of motion blur due to image persistence on the screen, independent of the fact that the duty cycle in a spatially multiplexed display is already greater than would be permitted in a temporally multiplexed display. Some recent technologies have been introduced to speed up the liquid-crystal response time (e.g. dynamic capacitance compensation), but these techniques can often cause artifacts of their own.⁹ Heesch *et al.* showed that the temporal aperture, or the temporal extent of the pixel aperture, can be used to predict flicker, motion blur, and judder.⁵ The work analyzed the effect of the temporal aperture on spatiotemporal aliases to show that short duty cycles reduce the appearance of blur but increase the visibility of flicker. This is consistent with our result.

The finding that dual-viewer strategy did not influence perceived motion artifacts confirms that the visibility of motion

artifacts is primarily dictated by the monocular images; i.e. there is little if any effect of the phase of stimulation between the two eyes.^{6,26} This is not the case, however, with flicker visibility. The phase of stimulation between the two eyes appears to play a role in flicker perception; there was a slight benefit of LXR over LR. Previous studies have shown that flicker-fusion rates are higher when illuminated frames are presented in phase in the two eyes, compared to when they are presented 180° out of phase.^{6,26} It therefore makes sense that frames presented 90° out of phase would cause a similar increase in flicker visibility.

It is also worth considering the fact that the temporal delay between left- and right-eye inputs often creates distortions in the perceived depth of moving objects because temporal delay is interpreted as spatial disparity. We confirmed previous work²⁷ that had shown that a longer interocular delay causes more depth distortion (data not shown). The LR driving mode (interocular delay 1/240s) therefore has at least one benefit over the LXR mode (interocular delay 1/120s).

5 Impact

This work assesses how a variety of display-related factors can influence the visibility of artifacts. The strongest factor influencing motion artifacts is the frame rate of the content depicted on the display. OLED technology offers rapid response times such that the bottleneck of the imaging system is no longer pixel response time. It is now possible to take advantage of multi-viewer temporal multiplexing and new approaches to generate content at high frame rates. One such method to extend the benefits of high-frame-rate displays is the development of improved motion-compensated, frame-rate conversion routines.^{28,29} These routines use sophisticated computer-vision algorithms that track the movement of objects in a scene and interpolate between consecutive frames to “fill in” the missing frames. The calculation of high-quality interpolated frames can have a substantial impact on reducing artifacts for fast-moving objects.

The discussion of motion clarity has been clouded by the widespread adoption of LCD displays with LED backlights. LEDs can be used to strobe the LCD display faster than the refresh rate, effectively creating a multi-flash driving mode intended to lower the sample-and-hold duty cycle of the display. Many display manufacturers report the LED backlight strobing frequency rather than the true refresh rate of the display, claiming to have refresh rates as high as 1440 Hz, even though the true refresh rate of the displays is much lower, at 120 or 240 Hz. Song *et al.* showed that motion blur is reduced on strobed-backlight LCDs compared to continuous-backlight LCDs due to the lower backlight duty cycle, but they did not provide a metric for the possible edge banding that could occur.³⁰ Some manufacturers offer a “flicker-free” mode for some of their OLED monitors, in which the signal is switched on and off twice or more within

one frame, equivalent to multiple flash.^{10,24} Though flicker may be reduced in this case, our research shows the potential downside of multiple-flash techniques in that they can exacerbate banding artifacts. A 240-Hz display with a backlight strobing at 1440 Hz does not increase the capture rate of the content and is therefore unlikely to substantially improve the appearance of motion compared to a 240-Hz display with a continuous-backlight LED. Samsung’s Clear Motion Rate, LG’s Motion Clarity Index, and Sony’s MotionFlow all report refresh rates significantly higher than the real refresh rate of the display.

Another method that has been proposed to reduce motion blur on sample-and-hold displays (both LCD and OLED) is black-data insertion.^{31,32} By doubling the frame rate and inserting a blank frame after each frame, this effectively reduces the duty cycle from ~1.0 to ~0.5. Shortening the duty cycle would be particularly easy for OLED displays because they have an immediate temporal response. Our research provides evidence that this driving mode should reduce the presence of motion artifacts. However, the display would be more susceptible to flicker, and the display would require a higher light output to negate the dimming effect of the black frames.

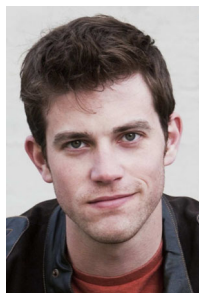
6 Conclusion

We examined a 240-Hz OLED display and found that a low flash number and low duty cycle reduces artifact visibility under tracking conditions with flicker being slightly more visible. This finding, combined with a clear benefit of higher capture rate, provides evidence to support the move to higher frame rate in television as well as cinema, which can utilize a lower flash number if the content has a higher frame rate. Our results also emphasize the importance of developing content for high-frame-rate displays.

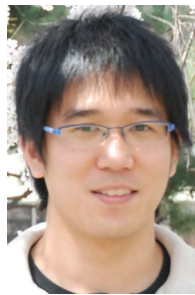
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