Motion Artifacts on 240Hz OLED Stereoscopic 3D Displays

Paul Johnson[1], Joohwan Kim[2], David M. Hoffman[3], Andres Vargas[1], Martin S. Banks[1,2]

[1]UC Berkeley - UCSF Graduate Program in Bioengineering

[2]University of California, Berkeley, Vision Science Program, 360 Minor Hall, Berkeley CA, USA

[3]Samsung Display Americas Lab, San Jose CA, USA

Abstract

We examined the visibility of motion artifacts—judder, motion blur, and edge banding—on a Samsung 240Hz stereoscopic 3D (S3D) OLED display. We determined the relative contributions of the frame rate of the content, update rate of the panel, duty cycle, and flash number. We compared the visibility of artifacts on the Samsung display with those on a 60Hz S3D LCD. Short duty cycles and low flash numbers reduce the visibility of motion artifacts.

Author Keywords

OLED; stereoscopic 3D; motion perception; motion sampling; frame rate.

1. Objective and Background

A general rule of thumb in display design asserts that motion looks smooth on displays with sufficiently high frame rates (Burr, Ross & Morrone, 1986). The majority of liquid-crystal displays (LCDs) and organic light-emitting diode (OLED) panels 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 actually needed to produce smooth motion across a range of object speeds (Watson, Ahumada & Farrell, 1986; Hoffman, Karasev & Banks, 2011).

To investigate artifacts on displays, one must make a distinction between capture rate and presentation rate. Capture rate is the number of unique images presented per second. Presentation rate is the number of images presented on the screen per second regardless of whether those images are unique or repeated (multi-flashed); presentation rate is capture rate multiplied by flash number. Capture rate tends to be the primary factor determining motion artifact visibility while presentation rate is the primary factor determining the visibility of flicker (Hoffman et al., 2011). Additionally, the duty cycle of image presentation—the fraction of the presentation interval in which imagery is illuminated—affects the visibility of motion artifacts and flicker (Watson et al., 1986; Hoffman et al., 2011). We examined how capture rate, presentation rate, and duty cycle affect the visibility of motion artifacts on a 240Hz OLED panel.

Figure 1 summarizes how different driving modes and viewing conditions affect the visibility of different types of motion artifacts. Consider the situation in which a viewer fixates a stationary point on the screen, and an object moves relative to that point. Because the display is digital, the object jumps across the retina in discrete steps (Figure 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*. 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 Figure 1. The eye movement causes the image to smear across the retina for the duration of the presentation interval; this is perceived as *motion blur* (Watson, 2013). The magnitude of the blur is proportional to the duration of each image presentation and thus motion blur is greater with longer duty cycles. In cases of multi-flash presentations, another effect—*edge banding*—can occur (Figure 1, bottom row) in which repeated presentation of an edge creates the appearance of ghost edges.

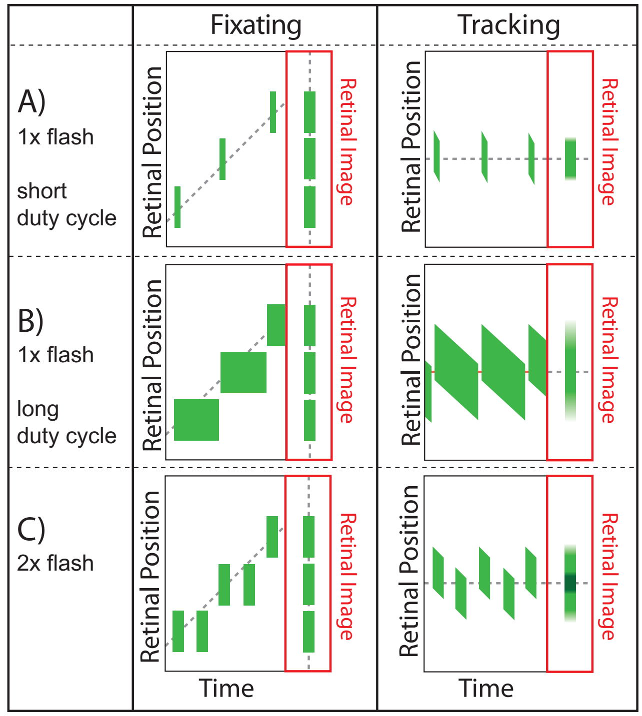

Figure 1. Retinal images with different display protocols, with fixating and eye tracking. The left panels show the motion along the retina over time when fixation is stationary. The panels on the right show the retinal motion when the object is tracked with a smooth-pursuit eye movement. A). Single flash (1x), short duty cycle (as in a stroboscopic display). B). Single flash, long duty cycle (as in a sample-and-hold display). C). Double flash (2x), medium duty cycle (similar to temporally multiplexed S3D display).

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 can be less. Liquid-crystal shutter glasses, which are often used to block left- and right-eye images, have some latency and therefore

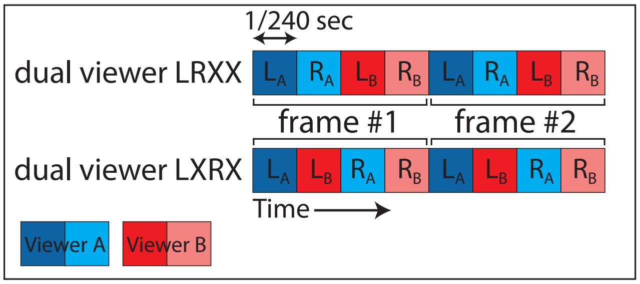

Figure 2. Dual-viewer modes possible with a 240Hz display. For a capture rate of 60Hz, stereoscopic content can be presented using either $L_AR_AL_BR_B$ (LRXX) or $L_AL_BR_AR_B$ (LXRX), where L_A and R_A are the left- and right-eye views for viewer A, L_B and R_B are the left- and right-eye views for viewer B, and X represents a blank sub-frame.

contain an inherent tradeoff between maximizing duty cycle and minimizing crosstalk: the bleeding of one eye's image into the other eye. To examine 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 can generate a duty cycle of nearly 1.0. Thus, motion blur should be more visible when tracking an object on a spatially multiplexed display than on a temporally multiplexed display.

Samsung's 240Hz S3D OLED display is fast enough to show faster than normal presentation rates and capture rates and thus could greatly reduce motion artifacts. The high frame rate also enables a dual-viewer S3D temporally multiplexed protocol in which two viewers can watch different stereoscopic video content on a single display. Two possible driving modes are $L_AR_AL_BR_B$ and $L_AL_BR_AR_B$, 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 (see Figure 2). We will refer to these protocols as LRXX and LXRX, respectively. We measured the visibility of motion artifacts in a series of psychophysical experiments. Many of the effects we observed are consistent with an analysis of spatiotemporal signals in the frequency domain (Adelson & Bergen, 1985; Watson et al., 1986; Hoffman et al., 2011).

2. Methods

To present stereo images, we used a prototype Samsung 240Hz S3D OLED panel that employs temporal multiplexing and a commercially available LCD panel (LG 47LM4700) that employs spatial multiplexing. Viewing distance was 3.18 times picture height such that one pixel subtended 1arcmin. We found the slowest object speed at which observers reported motion artifacts 50% of the time. The measurements were done both with stationary fixation and with tracking eye movements. For the LCD and OLED panels, we tested a range of capture and presentation protocols.

Figure 3 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 fixating condition, the fixation target was at screen center. The stimulus—a group of white squares moving horizontally at a constant speed—was visible for 1s. Following the presentation, subjects reported whether or not they saw motion artifacts in the moving squares. Subjects were directed to respond independently of the type of motion artifact perceived (e.g., blur, edge banding, or judder).

3. Results

Figure 4 plots the object speed on the OLED panel at which artifacts became visible as a function of capture rate. When only higher object speeds generated artifacts, it meant that artifacts were generally less visible. There was a clear effect of capture rate on artifact visibility in both the fixating and tracking cases. Artifacts were visible at a variety of capture rates including 60Hz, but became progressively less visible with increasing capture rate. Note that 120Hz is the highest possible capture rate for temporally multiplexed stereoscopic content.

We also investigated the effect of flash number (1X, 2X, and 4X) on the OLED panel. At the lowest capture rate of 30Hz, we tested the 2X and 4X flash protocols only; 1X flash induced substantial flicker. There was no significant difference between 2X and 4X. At a capture rate of 60Hz, only 1X and 2X flash was possible, and at the highest capture rate of 120Hz, only 1X flash was possible. For the fixating condition, there was essentially no effect of flash number on the visibility of motion artifacts, as we predict based on the retinal position model in Figure 1. For the tracking condition, however, motion looked markedly smoother with single flash than with double flash when the capture rate was 60Hz.

The effect of duty cycle on artifact visibility is shown in Figure 5. In the fixating case, duty cycle had no significant effect on motion artifacts. In the tracking case, 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.

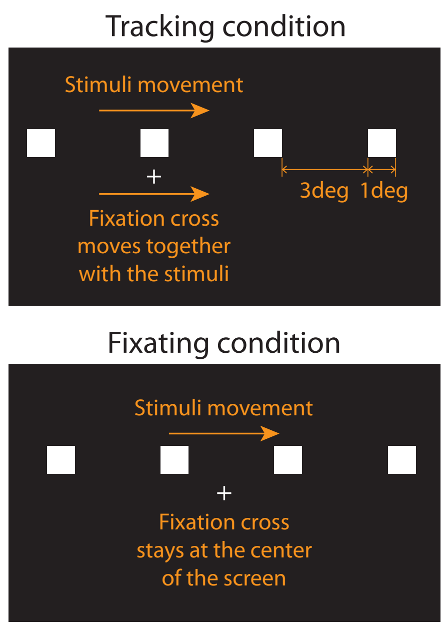

Figure 3. Stimulus and fixation target in the tracking and fixating conditions. A trial consisted of three parts: initial fixation, stimulus motion, and response collection. In the tracking condition, the fixation target moved with the same velocity as the squares across the center of the display. In the fixating condition, the fixation target remained stationary.

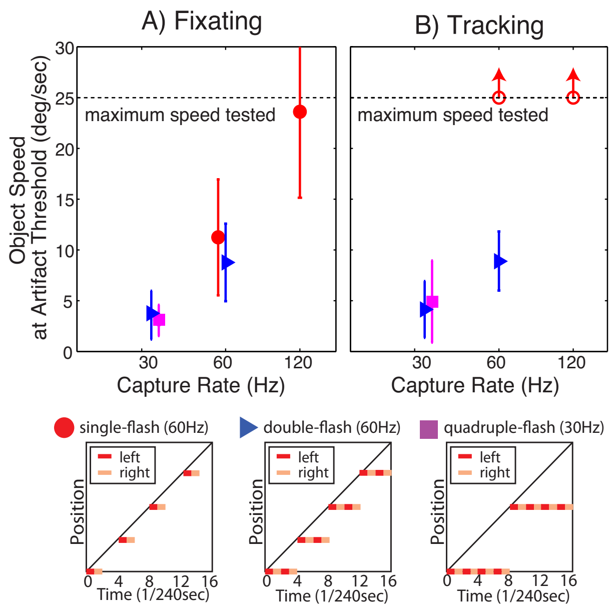

Figure 4. Effect of flash number on motion artifacts. The data have been averaged across five subjects. The object speed at which artifacts occurred 50% of the time is plotted as a function of capture rate. Higher ordinate values indicate smoother motion. Panels A and B correspond to fixating and tracking conditions, respectively. The open circles indicate that no motion artifacts were reported even at the highest speed tested. Error bars indicate 95% confidence intervals. The panels on the bottom illustrate the presentations over time for different flash numbers.

The shortest duty cycle of ~0.25 supported the fastest motion without artifacts. These observations are consistent with the retinal-image predictions in Figure 1.

We compared motion between the two possible dual-viewer modes, LXRX and LRXX, and found no significant difference (data not shown).

4. Discussion

We have shown that higher frame rates allow for smoother motion, but that frame rate is not the only predictor of the quality of visual experience. Duty cycle plays a role in the perception of blur if the viewer is tracking a moving object. But the severity of artifacts in this case will always be less than in the fixating case, even for a long duty cycle near 1.0. This means that motion artifacts in the fixating case provides a worst-case estimate of what the visual percept will be, but does not necessarily provide a metric for typical viewing experience. 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. The 240Hz OLED panel has a high enough frame rate to afford it some flexibility in how stereoscopic 60Hz content is presented in single-viewer mode. If eliminating flicker is a priority, then content could be presented with the maximum duty cycle of 0.5 (LLRR), or with double flash (LRLR). If eliminating motion artifacts is a priority, content could be presented with the lowest possible duty cycle of ~0.25 (LXRX or LRXX), greatly reducing motion blur during tracking.

As a general rule of thumb, presentation rates of 60Hz per eye or higher are used in displays to avoid visible flicker. 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 60Hz 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.

Multi-flash protocols, while helpful for minimizing flicker, can cause artifacts of their own. In digital 3D cinema, the popular RealD format presents 24Hz content using a triple-flash display protocol, for a presentation rate of 72Hz. 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 72Hz per eye or 144Hz 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 (content rate) at 48fps—have received mix feedback. Many viewers complain of a so-called "soap opera" effect that causes content to feel less cinematic, like a made-for-TV movie (Marks, 2012). To the best of our knowledge, this effect has not been rigorously characterized.

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 240Hz OLED display are effective at producing less motion artifacts than spatially multiplexed displays largely due to differences in the duty cycle.

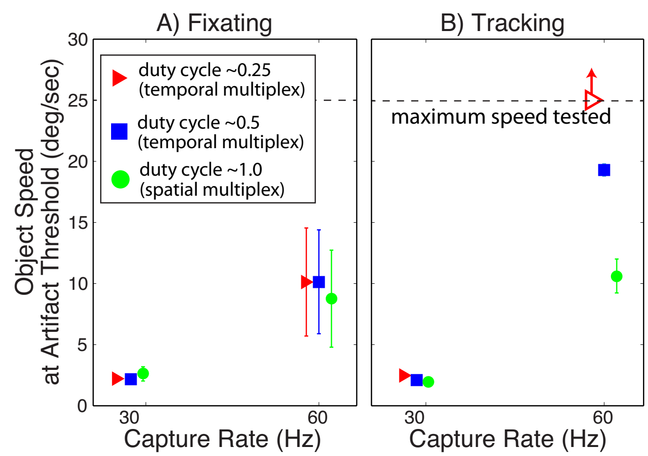

Figure 5. Effect of duty cycle on motion artifacts. Panel A corresponds to fixating conditions and Panel B corresponds to tracking conditions. The slowest object speed at which artifacts were reported on 50% of the trials is plotted as a function of capture rate. Red triangles and blue squares represent the temporal multiplexed display with duty cycles of ~0.25 and ~0.5, respectively. Green circles represent the spatial multiplexed display with a duty cycle of 1.0. We excluded one subject's data in Panel B 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 on this plot.

This finding, that the specific dual-viewer strategy did not influence the perceived motion artifacts indicates 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 (Cavonius, 1979; Hoffman et al., 2011). The key difference between LXRX and LRXX is interocular delay, or the temporal delay between left- and right-eye inputs. Interocular delay plays a large role in predicting depth distortion, in which a temporal delay is interpreted as disparity, but that is beyond the scope of this paper. There may also be slight differences in flicker perception between the two driving modes.

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 time 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 (e.g. Balram, 2008). The calculation of high-quality interpolated frames can have a substantial impact on reducing artifacts for fast-moving objects.

This research also shows the potential peril of simplistic frame rate conversion techniques such as multi-flash in that they can potentially exacerbate banding artifacts. The discussion of motion clarity has been clouded by the widespread adoption of LED backlight units of LCD displays. Although LEDs can be used to strobe the LCD panel at faster than the refresh rate, multiple flashes of the backlight without updating the image on the screen will not make motion appear smoother, and could cause the motion to appear worse.

We show that a lower flash number reduces artifact visibility under tracking conditions. This finding, combined with a clear benefit of higher capture rate, provides evidence to support the move to higher frame rate in cinema, which also utilizes a lower flash number. Our results emphasize the importance of developing displays with impulse-like response characteristics.

This OLED panel allows for a full frame switch every 1/240th of a second, enabling 60Hz per eye for up to four eyes. This has a number of useful applications but in particular could allow for a more immersive gaming experience. In multiplayer games, the screen is traditionally split in half to provide each player with their own view. The two dual-viewer modes mentioned in this paper would allow two different players to each have their own unique full-screen stereoscopic 3D viewing experience.

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7. References

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