

Enhancing VRR Flicker Index Using Time-Domain Analysis

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Abstract

The cutting-edge displays are emerging with a technology called VRR (Variable Refresh Rate), which supports a wider range of refresh rates. Although VRR can reduce power consumption, users may experience flickering issues as the display refresh rate varies depending on the image characteristics (e.g. speed). Therefore, more accurate method for predicting flicker prediction in VRR displays is necessary. This research purposes a flicker prediction model for VRR displays. First, we defined the situation that VRR flicker appears through measuring the waveforms in two actual VRR displays. Next, we identified the two factors affecting the perception of VRR flicker and we conducted the psychophysics experiment. Finally, we introduce time-domain analysis using Impulse Response Function (IRF) to capture aperiodic luminance fluctuations and predict the perception of VRR flicker. These results demonstrate that time-domain analysis with an appropriate weighting function offer a more accurate prediction of flicker perception in VRR displays.

Author Keywords

VRR display; VRR flicker; Time-domain analysis; IRF.

1. Introduction

Recent displays with VRR technology offer a wider range of refresh rates, exceeding both lower and higher than the conventional 60Hz limit. High refresh rates (HRR) enhance image quality for dynamic content but increase power consumption. To mitigate this, VRR displays automatically lower the refresh rate for static content (e.g., web browsing, reading) or dynamically adjust it based on content frame rates (e.g., games with slow-moving scenes).

Unfortunately, VRR technology may introduce flicker issues for users. The first issue is flicker at a single refresh rate below 60Hz. This occurs because the critical flicker fusion frequency (CFF) typically falls within the 50-60 Hz range. CFF is defined as the frequency above which the visual stimulus appears steady and continuous. If the refresh rate is lowered below 60Hz for reducing power consumption, flicker may occur – henceforth, we refer it as static flicker. However, various studies on the perception of static flicker have been conducted in lighting and display industries. Static flicker can be interpretable through the flicker indices. In the international standards, there are some indices that represent the amount of flicker on displays: JEITA and Flicker Visibility (F.V.) [1] and Flicker Modulation Amplitude (FMA) [2]. Although the formulas for these three indices are different, all indices have two things in common. Waveforms containing periodic modulation in luminance are decomposed in the frequency domain, and a weighing functions is applied to reflect the temporal characteristics of the Human Vision System (HVS), whose sensitivity varies with frequency. Therefore, we can predict the users' experience of static flicker by calculating various flicker indices.

The second flicker issue with VRR displays is that transient luminance fluctuations can occur when the refresh rate changes. This happens because it is very difficult to maintain consistent luminance at the same gray level is between two different refresh rates [3]. When using actual VRR displays, users may encounter these transient fluctuations aperiodically. Especially, in gaming situation, the speed of content depends on the user's interaction. Since it is not possible to predict all user response patterns, this kind of flicker is unpredictable – henceforth, we refer it as VRR flicker. When interpreting the amount of VRR flicker with traditional flicker prediction methods, there is difficulty because they focus on periodic luminance variation. Therefore, a new approach for VRR flicker prediction model is necessary for multiple refresh rates employed by VRR displays.

This study is initiated to interpret non-periodic VRR flicker using time-domain analysis. First, we measured the waveforms of four VRR monitors based on measurement introduced by VESA Display Port Adaptive Sync (DP-ADAPTIVE SYNC) [4]. At the same time, we observed the user experience of VRR flicker. Based on a previous work [3] and VESA measurements, we identified a specific situation in which an abrupt transition between two refresh rates can cause flicker in VRR displays. To investigate this situation, we designed a controlled experiment with two independent variables: the switching speed between two refresh rates and the luminance difference between the two refresh rates. Finally, we propose a predictive flicker model for multiple refresh rates with time-domain analysis.

2. Methodology

VRR Flicker Detection test using VESA VRR Flicker Measurement tool: The VESA Display Port Adaptive Sync standard defines various scenarios for variable refresh rate testing, including zigzag sweep, abrupt switching (“Square-wave”), random video frame rate and sine-wave sweep. We used the VESA tool to measure the waveforms of four VRR displays (model: PG27AQN, AW2521H, 32GS95UE, AW3423DW). The luminance of the test image in the VESA tool was set to approximately 40cd/m² at 128 gray. To check for VRR flicker at lower luminance than 40cd/m², we adjusted luminance of the test image to 6cd/m² and 10cd/m² using the monitor's brightness settings. We obtained forty waveforms of 10 seconds duration using a measurement instrument (Admesy, Prometheus LF) as shown in Fig1 and Fig2. At the same time, we observed the perception of VRR flicker in all cases. A total of six subjects participated. Participants answered YES or NO whether they detected flicker or flash on the monitors during VESA VRR flicker testing. Each VRR scenario was presented eight times.

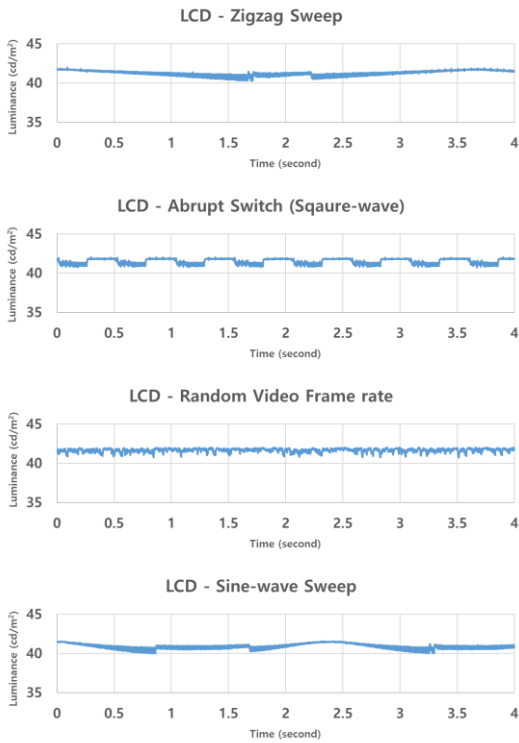


Figure 1. Measured waveforms (PG27AQN) for VESA VRR scenarios.

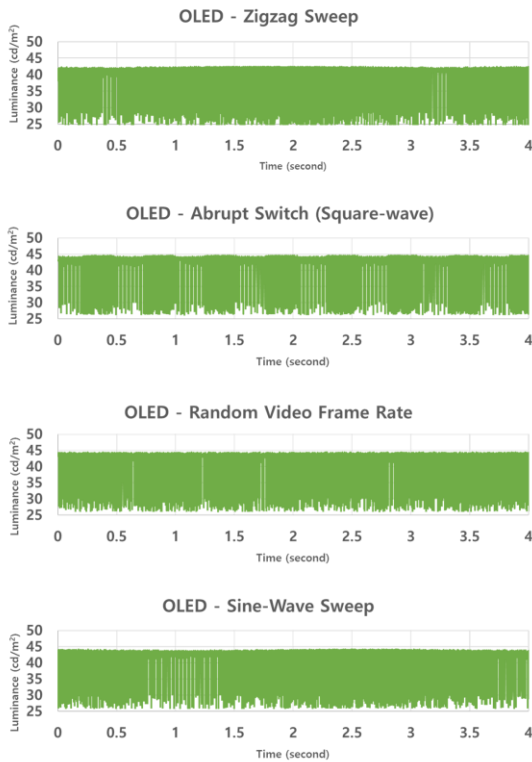


Figure 2. VRR waveforms in 32GS95UE.

Table 1 shows that flicker detection ratios in all cases, where 1 manes that all participants always detect flicker across eight times. Although the maximum and the minimum luminance were the same in four scenarios, the flicker detection rates varied depending on the VRR scenario type. The result indicates that participants detected flicker especially in two VRR scenarios, square-wave and random video frame rate. Comparing the waveforms and flicker detection rates, it is the sudden luminance change due to rapid change in the refresh rate that evoke the flicker perception. Meanwhile, a gradual luminance change does not cause flicker perception. This means that not only the luminance difference between two refresh rates but also the change speed are the important factors in VRR flicker perception.

Table 1. The ratio of detecting flicker on the monitors during VESA VRR testing (': cannot express 6cd/m²).

	cd/m ²	Zigzag	Square	Random	Sine
LCD1*	10	0.000	0.000	0.000	0.000
	40	0.000	0.000	0.000	0.000
LCD2*	10	0.000	0.604	0.563	0.021
	40	0.063	0.792	0.833	0.167
OLED1	6	0.025	1.000	1.000	0.005
	10	0.018	0.875	0.708	0.021
	40	0.021	0.000	0.000	0.021
OLED2	6	0.125	0.857	0.989	0.063
	10	0.089	0.589	0.607	0.188
	40	0.054	0.062	0.054	0.071

Controlled Experiment of Detecting VRR flicker: To verify the two factors of luminance difference and change speed in VRR flicker, we conducted a controlled psychophysical experiment. To mimick the square-wave senario alternating between two refresh rates, a gray image with 60Hz or 120Hz presented on the monitor alternately. We chose the refresh rates above 60Hz to eliminate flicker for each single refresh rate. We used a display with OLED 240Hz (model: 32GS95UE, 32-inch). By controlling subtle luminance of four frames (for 60Hz image) or two frame (for 120Hz), participants are able to perceive the images with 60Hz or 120Hz (Fig3). The luminance difference (A-B in Fig3) within one frame is set identically for 60Hz and 120 Hz images.

The first variable is the difference in luminance between 60Hz and 120Hz. There are three levels of difference: almost the same (about 0.1%), small D (0.6%), and large D (1.3%). The second variable is the speed of change, which is controlled by the duraion of each refresh rate. In the fast change condition, the image of each refresh rate is presented for 100msec. In the control change condition, the duration is 200msec, which is used in VESA measurement (Fig4 and Fig5). The average luminance of all stimuli was approximately 40cd/m².

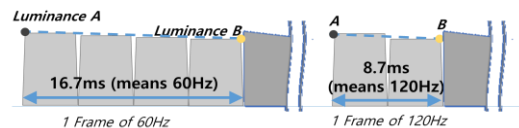


Figure 3. Conceptual waveforms to mimic a 60Hz or a 120Hz image using a 240Hz display.

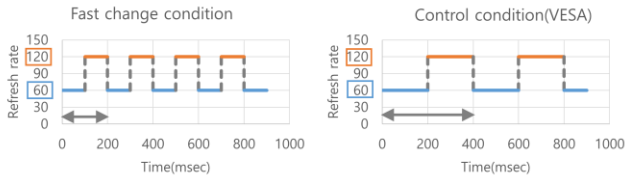


Figure 4. Two conditions in the speed of change between 60Hz and 120Hz based on the square-wave scenario.

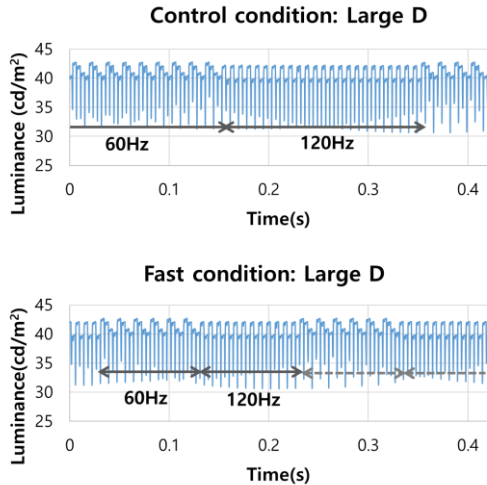


Figure 5. Measured waveforms for two speed conditions with large luminance difference between 60Hz and 120Hz.

Participants were asked to detect flickering during looking at the stimulus. The test stimulus was presented for 5s, and participant pressed a keyboard to respond their perception (←: no flicker, →: detect flickering). The order of all stimuli was randomized by each participants. Each stimulus was presented five times. Total trial was thirty (change speed (2) x difference (3) x repetition (5)). The experiment included eight subjects.

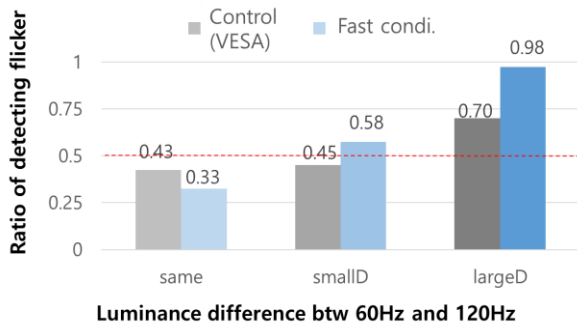


Figure 6. Flicker detection ratio depending on the luminance difference between two refresh rates and change speed.

Figure 6 shows the average ratios for detecting flicker in two speed conditions. Although the three levels of luminance difference between 60Hz and 120Hz were similar in two speed condition, flicker detection ratio differed depending on the change speed, with more flicker perceived in the fast condition. This result can be explained by the Temporal Contrast

Sensitivity Functions (TCSF). Considering switching from 60Hz to 120Hz as one cycle in time, the fast condition contains 5 cycle per minute. That is, the change speed in the fast condition corresponds to 5Hz in the frequency domain. Similarly, the speed in the control condition corresponds to 2.5Hz. Since the sensitivity of 5Hz is higher than that of 2.5Hz in the TCSF [5,6], this experimental result is consistent with the HVS system. This result implies that when users view an image with changing refresh rates in VRR situation, the luminance differences among refresh rates can cause flicker depending on the switching speed between multiple refresh rates. Therefore, it is required to predict users' flicker perception.

3. VRR Flicker Index: Time-Domain Analysis

This study attempts to interpret human responses in VRR situation using the concept of human visual causality [7-9]. This principle states that humans cannot react to an event before it occurs. In the context of VRR displays, this implies that viewers cannot perceive flicker until a change in luminance arises due to a shift in refresh rates. Most of the VRR flicker detected by users when using actual VRR displays appear non-periodic, similar to the scenario of random video frame rate in VESA. In order to predict VRR flicker, therefore, it is necessary to capture a non-periodic variation in the VRR waveforms preserving the rule of causality.

In order to reflect not only human temporal sensitivity but also the human visual causality rule, we chose the time-domain analysis with an impulse-response function (IRF), instead of the frequency-domain analysis with TCSF. Since IRF can interpret the detection probability of consecutive luminance changes [8], we tried to predict flicker perception when luminance differences due to changes in the display refresh rates appear non-periodically. Previous study has revealed that when using the time-domain analysis, the calculated VRR flicker index remained stable in VRR situations, even though the waveforms contain various refresh rates and the change in the refresh rate appeared at any time in the waveform data [10]. Additionally, IRF is proper for display situations. It is revealed that the uniform field stimulus without spatial contrast, commonly used as a flicker stimulus in displays, have different effect on the inhibitory signals [6,11]. This may lead to a different interpretation than the one that assumes spatial frequency of 0 in TCSF. Therefore, based on the previous studies using the uniform stimulus in the human temporal perception experiment [12, 13], we decided to use IRF curve as a weighting function. This filter consists of a positive section and a negative section to mimic human responses to temporal stimuli.

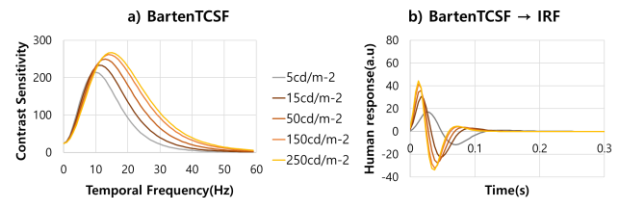


Figure 7. 1) The curves of BartenTCSF depending on luminance, 2) the IRF curves converted from BartenTCSF

To obtain the IRF curve for our VRR flicker index, we transform the TCSF curve into an IRF curve. Stork and Falk [7] were able to restore the phase information based on Kramers-

Kröning relations and to convert Kelly TCSF into IRF. In the same way, we try to convert the TCSF curve we chose to convert is the BartenTCSF model [11]. This model reflects that human sensitivity to frequency changes with the luminance and size of stimulus. If we put the information about size (unit: visual angle) and luminance (cd/m²) to the BartenTCSF model, the corresponding TCSF curve will be drawn. Figure 7 - a) shows the various examples of TCSF curves depending luminance levels. Figure 7 - b) shows the IRF curves converted from the Barten TCSF curves.

Developing the VRR flicker Index: To quantify the amount of VRR flicker, we replace the the process of performing FFT and applying TCSF in the IEC flicker index calculation into two steps: the first step is to draw an appropriate TCSF curve that corresponds to the image attributes of the display; the second step is to convert the selected TCSF curve into an IRF curve, which is a time-domain filter [14]. This IRF does the convolution with the waveforms. After convolving the waveforms measured on the display with the converted IRF as a weighting function, we calculated the RMS value in the filtered graph, which represents human response to spatially uniform stimulus. Since our previous studies revealed that the flicker index of duty waveform was overestimated than perceived flicker [15], we normalized the filter graph by the peak luminance before calculating a RMS value.

To verify that our VRR flicker index has high perceptual congruence with an actual VRR Flicker, we evaluated the correlation between our VRR flicker index and flicker detection data in two VRR flicker testing, where the display refresh rate dynamically changes. For calculating VRR index, we used measured luminance values and calculated visual angle values (viewing distance: 0.6m). Table 2 shows the correlation values (r) between flicker detection rates in two VRR flicker detection testing and the values derived from each flicker index. Since JEITA only used the information of the main frequency of the waveform, it cannot interpret VRR waveforms with various refresh rates. On the other hand, since our index interprets the continuous onset information of the stimulus, it is predictive for users' VRR flicker detection.

Table 2. The correlation (r) between VRR flicker indices and our experimental results.

correlation(r)	JEITA	Proposed Index
Result of VESA testing	0.149	0.942
Result of controlled exp.	0.616	0.967

4. Conclusion

While prior research has explored the application of IRFs to analyze periodic luminance fluctuations [9,16] we propose that IRFs hold particular promise as weighting functions for VRR flicker prediction. This stems from their ability to reveal the causal relationship between luminance changes and human responses. Additionally, IRFs can effectively explain flicker perception for uniform-field stimuli that lack spatial contrast, a common scenario in display evaluation. Comparisons between perceived flicker and the flicker indices derived from the two

models revealed variations in explanatory power across luminance difference and switching speed experiments. These findings suggest the need for further research and industry discussions to develop a model with the strongest explanatory capability for VRR flicker prediction.

5. References

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