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Time-Domain Analysis for Variable-Refresh-Rate Display Flicker

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Abstract

When using VRR displays, one of the recent topics of discussion among users is the flicker that appears when the refresh rate changes. Users may experience VRR flicker when transient luminance fluctuates during refresh rate changes. Unlike the flicker index used for a single static frequency, transient fluctuations on VRR displays are aperiodic and unpredictable. To explain the aperiodic property of VRR flicker, we considered the concept of human visual causality. In the aspect of interpreting the onset of the human response to luminance change in VRR waveform, we compared the results between frequency domain analysis and time domain analysis. Based on the result of testing the preservation of visual causality, we suggest a new VRR flicker index. To verify proposed VRR index, we measured VRR waveforms and test users' flicker perception using the VESA VRR measurement tool. Additionally, in the controlled psychophysical experiment, we compared the users' response with our proposed VRR index. As the result, the VRR index based on the time domain analysis well explained users' experience in VRR displays.

Introduction

Flicker, a perceptual phenomenon caused by variations in light intensity over time, has traditionally been defined as a periodic changes. The link between flicker and periodic changes in luminance is likely due to the fact that the light source has always emitted a single frequency of light unless it fails or breaks. This also applied to displays before the introduction of a Variable-Refresh-Rate (VRR) technology. Given the narrow definition of flicker, it is unclear whether the artifact at VRR situation can ever be called flicker, since it is not periodic and it contains multiple refresh rates. However, users and reviewer in display review sites refer to VRR flicker as an image artifact that occurs in VRR displays when the monitor's refresh rate changes. In addition, flicker is not limited to periodic fluctuations. The Commission International de l'Éclairage (CIE) also offer a broader definition including non-periodic fluctuations [1,2]. Therefore, the term VRR flicker can be used when we experience flashing or twinkling in various VRR usage scenario in order to distinguish it from static flicker due to a single refresh rate.

Although there are various causes of VRR flicker, one of recent topics for users is the flicker that appears when the refresh rate is change. Users perceive VRR Flicker when transient luminance fluctuations occur during a refresh rate change. This is because it is difficult to maintaining consistent luminance at the same gray level between refresh rates [3, 4]. The wider the interval between two refresh rates, the larger the luminance difference when the refresh rate is switched. Taking advantage of this trend in reverse, some display manufacturers provide anti-flicker settings that narrow the refresh rate range of VRR displays. For an OLED 240Hz VRR monitor (model: XG27AQDMG), for example, the minimum refresh rate is 40Hz when anti-flicker is off, but the minimum refresh rate increase to 200Hz when the anti-flicker option is selected as strong mode. Since the changeable frequency range between the maximum and the minimum refresh rate is 200 ~ 240Hz, luminance difference between refresh rates is reduced. As the result, users cannot detect VRR flicker, but the monitor's power consumption may increase.

Along with developing technologies to reduce VRR flicker, it is also necessary to develop an index that represents magnitude of VRR flicker. This is because the current level of a technology can be examined using the VRR flicker index value. In particular, since flicker is related to health problems [5], we should provide users and display manufacturers with the VRR flicker levels on various VRR displays. Because the field of VRR flicker research is relatively new compared to a single static frequency, there are various attempt to interpret VRR flicker rather than there being a main stream. In the case of VESA, it provides four special scenarios to measure VRR flicker, but it still uses JEITA, which is a flicker index that describe flicker due to a single static frequency. On the other hands, Minolta has propose a new VRR flicker value in its new measurement instrument, CA-P527. In the academic approach, Cai et al. propose a special TCSF, called as elaTCSF to explain perception of VRR flicker [6].

Unlike the flicker index used for a single static frequency, transient fluctuations on VRR displays are aperiodic and unpredictable, making it difficult to predict VRR flicker with traditional flicker prediction methods that focus on periodic variations. To explain aperiodic property, we considered the concept of human visual causality [7-9]. This principle states that humans cannot react to an event before it occurs. In the usage situation of VRR displays, this implies that viewers cannot perceive flicker until a change in luminance arises due to a shift in refresh rates.

In order to reflect the principle of visual causality to a VRR flicker index, we approach to a time-domain analysis with an Impulse Response Function (IRF). The concept of causality inherent in IRFs [7] allows for prediction of flicker perception even when transient luminance changes occur aperiodically. Prior research has shown that time-domain analysis using IRFs produces stable results in VRR scenarios, even with waveforms containing various refresh rates and unpredictable refresh rate switching events [10]. Additionally, IRFs are well-suited for display applications. Studies have revealed that uniform field stimuli, commonly used for flicker evaluation in displays and lacking spatial contrast, can have distinct effects on inhibitory signals compared to stimuli with spatial information [11,12]. This distinction may lead to interpretations that deviate from those based on the assumption of zero spatial frequency within a TCSF. Therefore, informed by previous studies employing uniform stimuli in human temporal perception experiments [13,14], we opted to utilize an IRF curve as the weighting function.

In the next paragraph, we will compare the results from the frequency-domain analysis and time-domain analysis on the aspect of interpreting the timing of human response to luminance change in VRR waveform. Since a measured waveform on an actual display may contain various noise, we use a simulated VRR waveform. Base on the result, we suggest the VRR flicker index. To verify the good match between users' VRR flicker perception and the VRR flicker index, we measured VRR waveforms and test users' flicker perception using the VESA VRR measurement tool. In addition, in the controlled psychophysical experiment, we compared the users' response with our proposed VRR index.

Test for preserving visual causality

To accurately describe unpredictable events, a filter interpreting VRR waveforms must be able to capture the time of occurrence of the events. In order to compare the difference in capturing the timing of human response to transient luminance changes in VRR waveforms, we observed the graphs after applying two types of HVS filters, TCSF based on the frequency domain analysis and IRF based on the time-domain analysis, to the VRR waveforms. For the fair comparison, we chose the Kelly's TCSF introduced in the IEC standard and used the IRF converted from the Kelly's TCSF. The TCSF curves can be converted to IRF curves to incorporate phase information. Stork and Falk [7] demonstrated the recovery of phase information using Kramers-Kröning relations and the subsequent conversion of Kelly's TCSF into an IRF. Following this approach, we converted the IEC Kelly's TCSF curve to an IRF curves (Figure1).

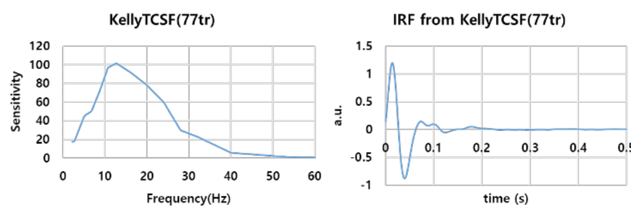


Figure 1. *Kelly's TSCF in IEC Flicker Measurement and IRF converted from Kelly's. We interpolated the sensitivity between points on the TCSF.*

Next, we simulated the VRR waveform based on the VESA VRR measurement method. Among four scenarios in VESA, we chose the square wave change for the VRR refresh rate, even though two scenarios, square wave and random frame rate, seem to be similar to the actual usage situation. To minimize the effect of static flicker at each refresh rate, we selected two refresh rates, 90Hz and 240Hz, which are higher than 60Hz. The average luminance is 40 cd/m² for the duration of 240Hz, but we manipulated the luminance difference between 90 Hz and 240 Hz to two levels: 40.4cd/m^2 (+1%) and 44cd/m^2 (+10%) (Figure 2). The switching frequency was at two levels: 0.5 Hz and 2.5Hz. It is noteworthy that the same simulation waveforms were used, and only the magnitude of the luminance difference varied during the refresh rate switching events.

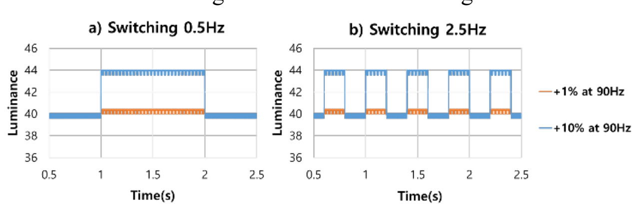


Figure 2. *Simulated VRR waveforms switching between 90Hz and 240Hz*

We compared the filtered graphs showing the changes in human responses. In the frequency domain analysis, the method was same as the IEC flicker index until the step before calculating the index [15]. In the time domain analysis, the simulated waveforms were convolved with the IRF. The waveform graph and the filtered graph were overlaid to compare the start time of the waveform change and the human response. In the case of the IRF, a 500ms length was convolved, so the start time of the filtered graph was adjust because the filtered graph was shortened by 500ms.

Result of Frequency-Domain Analysis

Figure 3 shows the filtered graph after performing iFFT. The red arrows point to the start point of changes in the VRR waveforms and the blue arrows to the start point of changes in the filtered graph.

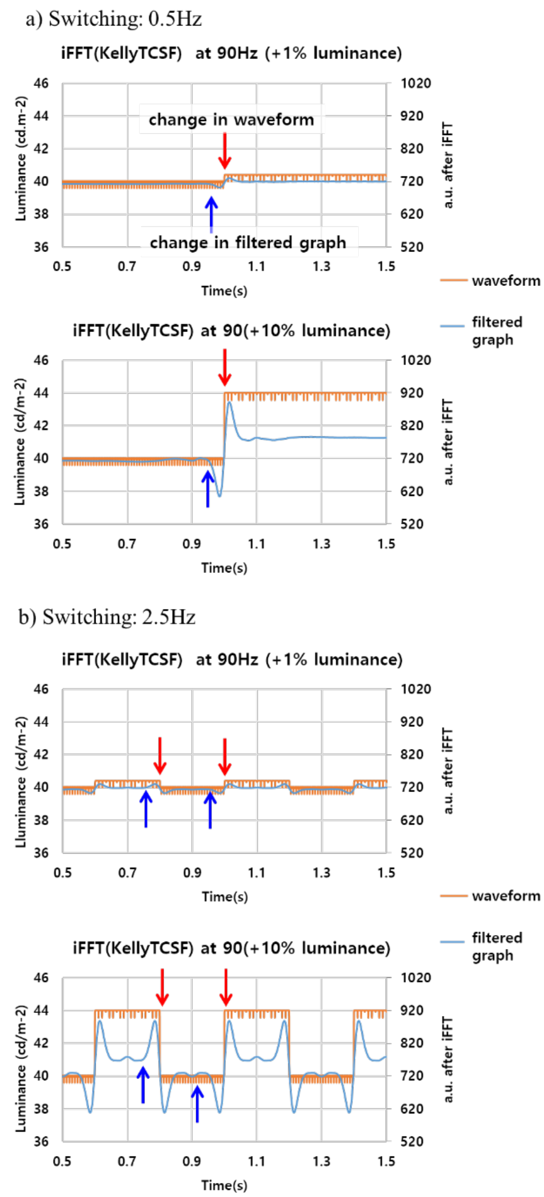


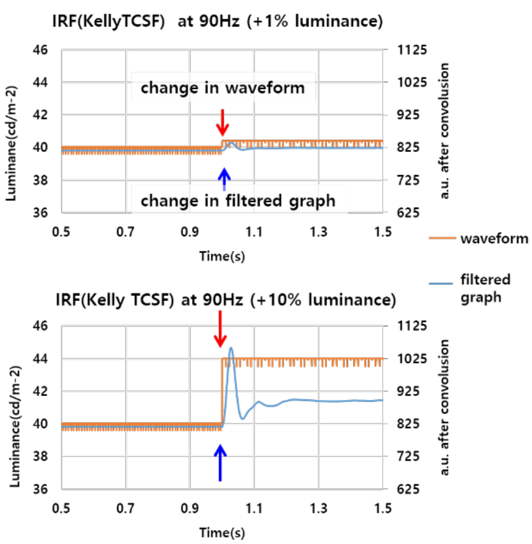
Figure 3. *The filtered graph with iFFT using Kelly's TCSF*

As the result, the start point of changes in human response precedes the change point of waveform. Interpreting the concept of visual causality, this means that the human response begins before the luminance differences appear in the VRR waveform. The larger the luminance difference when switching the refresh rates, the clearer the tendency of visual causality to break down. When a large modulation appears in the human response, the change point appears to move to an earlier time than when there is a small modulation. Considering the actual VRR usage environment, when various luminance differences occur, the human response will be mixed in the filtered graph before the luminance change, making the prediction of VRR flicker inaccurate. Moreover, when extracting data from the VRR waveform in the actual usage, it is difficult to determine the starting point because human responses appears to differ depending on the amount of luminance difference in the VRR waveforms.

Result of Time-Domain Analysis

Figure 4 show the filtered graph after convolving the waveform with the IRF. As the result, the onset of the changes in the VRR waveforms and the human responses were almost the same. Even if the luminance difference is large when switching the refresh rates, the onset of the change in the human responses begins when the luminance differences occurring in the waveforms. This implies that time-domain filter can capture the time of occurrence of the events.

a) Switching: 0.5Hz



b) Switching: 2.5Hz

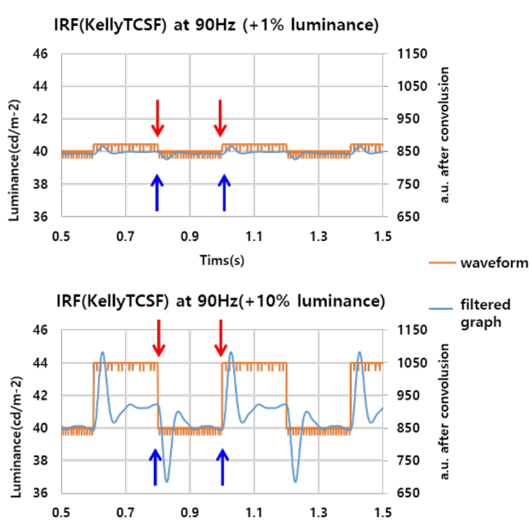


Figure 4. *The filtered graph with IRFs from Kelly's TCSF*

Implication of testing visual causality

The results of the test for preserving visual causality stem from the inherent limitations of frequency domain analysis. TCSFs, lacking phase information, cannot capture the temporal aspects of luminance changes, specifically the timing of their onset [7,10]. This limitation has a minimal impact on flicker prediction at single static refresh rates, where luminance fluctuations are periodic. However, in the VRR scenarios, the aperiodic nature of luminance variations across dynamically changing refresh rates introduces significant challenges for predicting flicker perception. Therefore, we propose the VRR flicker index using IRF instead of TCSF.

Developing VRR flicker Index using IRF

Several static flicker indices are defined within international display measurement standards to quantify perceived flicker on displays. These include JEITA and Flicker Visibility from the IDMS (Information Display Measurement Standard) [16], released by ICDM (International Committee for Display Metrology), and Flicker Modulation Amplitude from the IEC (International Elecrotechnical Commission) [15]. While the specific formulas for each index differ, they all share a common approach: frequency domain analysis using the Fast Fourier Transform (FFT) in conjunction with weighting functions (Figure 5).

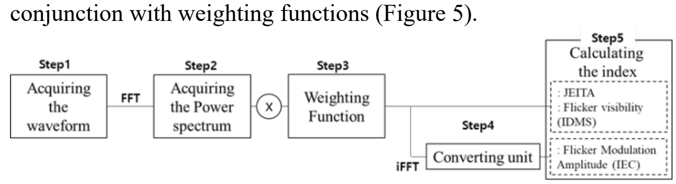


Figure 5. *The processes of statidlwp c flicker calculation methods*

Our proposed method replaces the traditional steps of FFT and TCSF application with following two-stage process (Figure 6):

1. Generate a TCSF Curve
2. Convert TCSF Curve to IRF and Perform Convolution

The first stage involves selecting a TCSF curve that accurately describes the combined influences of luminance and size on the display image. This is because both luminance and size affect the sensitivity in flicker perception [17]. In this study, Barten's TCSF model [12] and Matiuk's elaTCSF model [6] are both suitable candidates, offering the ability to incorporate these factors [17]. By inputting the stimulus size (visual angle) and luminance (cd/m²), the chosen model generates a corresponding TCSF. In the second stage, selected TCSF curve is converted into an IRF curve to account for time information, crucial for precise VRR flicker prediction. This conversion process recovers the missing phase data using Kramers-Kröning relations [7].

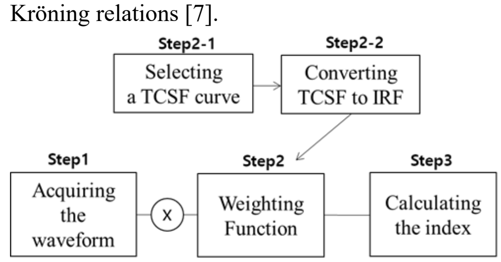


Figure 6. *The process of the VRR flicker calculation method*

Figure 6 shows the overall process for calculating the VRR flicker index. The IRF converted from BartenTCSF's curve or elaTCSF's curve serves as a human response filter based on the time-domain filter. We perform a convolution between the VRR waveforms and the converted IRF to effectively apply the filter. We calculated the RMS value in the filtered graph after convolution. To solve the overestimation of perceived flicker observed in previous studies using the flicker index of duty cycle waveforms [18], the filter graph is normalized by the peak luminance before the RMS calculation. We call this index "the dynamic flicker index (D.Flicker)" because the VRR waveforms contain multiple refresh rates and the refresh rates change dynamically. It is also an opposite concept of traditional flicker at static single refresh rate.

Validation with Users' VRR Flicker Detection

VESA VRR Flicker test data

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 monitors (model: PG27AQN, AW2521H, 32GS95UE, and AW3423DW). The luminance of the test image in the VESA tool was set to approximately 40cd/m^2 at 128 gray. To check for VRR flicker at lower luminance than 40cd/m^2, we adjusted luminance of the test image to 6cd/m^2 and 10cd/m^2 using the monitor's brightness settings. We obtained forty waveforms of 10 seconds duration using a measurement instrument (Admesy, Prometheus LF) (Figure7). 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. The viewing distance was 60cm (visual angle of three monitors: 31.3°, 31.6, and 36.7°).

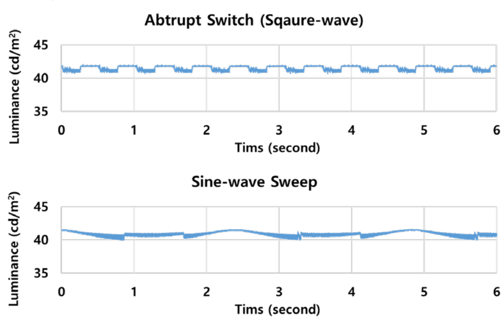


Figure 7. *Examples of the VRR waveform presented by the VESA tool.*

To compare the perceptual congruence between VRR flicker perception and the VRR flicker index, we used three types of indices: JEITA proposed by VESA, VRR flicker value (VRRF) measured by CA-527, and our proposed VRR flicker index (D.Flicker). The VRRF measured by CA-527 consist of three values: maximum, average, and minimum. The D.Flicker was calculated using two IRF curves converted from Barten's TCSF and elaTCSF. A total six values were used. Before the analysis, the waveforms in one LCD monitor were excluded because no one detected VRR flicker. A total of 32 waveforms were analyzed.

Figure 8 show the scatter plot of various indices and participants' VRR flicker detection ratios. The values on the x-axis are the values of the VRR flicker indices. The y-axis is the VRR flicker detection ratio, where 1 means that all participant detected VRR flicker all eight times. Except for JEITA, the other indices seems to have a linear relationship. Using Minitab17, we performed ta Pearson correlation analysis. Table 1 shows the correlation coefficients (r) between the six VRR flicker indices and participants' VRR flicker detection ratios. VRRF and D.Flicker have a statistically significant relationship with participants' experience, but not with JEITA. Of the three values of VRRF, the maximum value shows the higher correlation than the average or minimum values. For D.Flicker, when using the IRF curves transformed from Barten's TCSF, perceptual congruence increases.

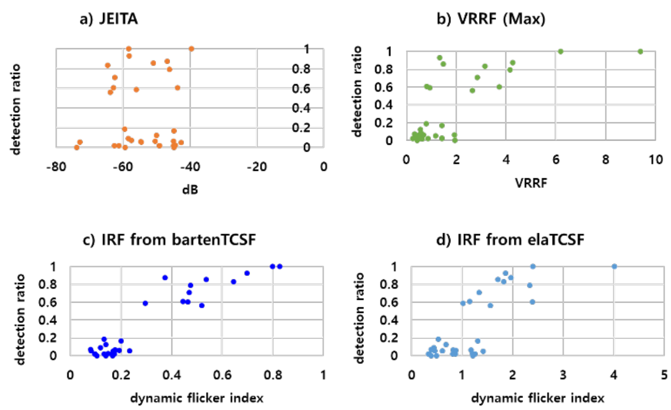


Figure 8. *IS&T logo (note the use of bold and italics)*

Table 1. The correlation coefficients (*r*) and *p*-values between VRR flicker index and VRR flicker detection ratios

	JEITA	*VRRF*			*D.Flicker*	
		avg	*Max*	*Min*	*Barten TCSF*	*ela-TCSF*
r (*p*)	*0.031* (*0.864*)	*0.740* (*>0.01*)	*0.728* (*>0.01*)	*0.669* (*>0.01*)	*0.938* (*>0.01*)	*0.793* (*>0.01*)

Controlled Experiment for Switching Speed

Since the VESA VRR test tool only has one abrupt switching condition, where each refresh rate is maintained for 200ms, we performed controlled experiment to observe the effect of switching refresh rate speed. To mimic the square-wave scenario 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 (Figure 9). The luminance difference (A-B in Fig3) within one frame is set identically for 60Hz and 120 Hz images.

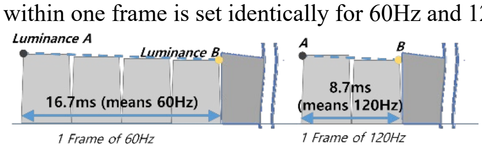


Figure 9. *Conceptual waveforms to mimic a 60Hz or a 120Hz image using a 240Hz display*

The first variable is the average luminance of overall VRR waveforms: 4, 20, and 40cd/m^2. The second variable is the luminance difference between 60Hz and 120Hz. There are three levels of difference: almost the same (0 ~ 0.4%), small D (0.6~0.9%), and large D (1.3~1.6%). The third variable is the speed of switching, which is controlled by the duration 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 (Figure 10). 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. The speed in the control condition corresponds to 2.5Hz.

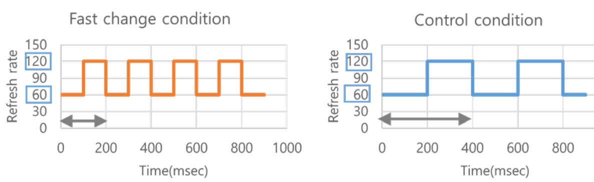


***Figure 10.** Two switch speed conditions between 60 and 120Hz*

The task of participants was to detect VRR flicker. 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 per one luminance condition was thirty (change speed (2) x difference (3) x repetition (5)). The experiment included eight subjects for the condition of 40cd/m^2 and six subjects for the other conditions. To compare the perceptual congruence between VRR flicker perception and the VRR flicker index, we used two VRR flicker indices: JEITA and D.Flicker with Barten's TCSF.

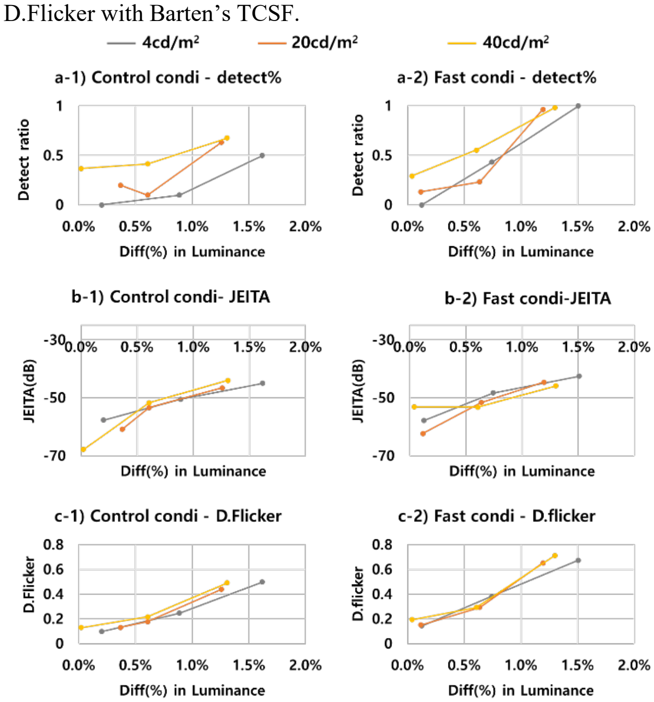


***Figure 11.** VRR flicker detection ratios, JEITA and D.Flicker (proposed index)*

Figure 11 shows the VRR flicker detection ratio, JETA, and D.Flicker. The x-axis presents the luminance difference between 60Hz and 120Hz. As a result, although the three levels of luminance difference between 60Hz and 120Hz were similar in two speed condition, VRR flicker detection ratio differed depending on the switch speed, with more flicker perceived in the fast condition. In addition, the dimmer the stimulus, the less frequently participants detect VRR flicker. Regarding the perceptual congruence between VRR flicker detection ratios and the VRR flicker indices, our proposed index appears to be more consistent than JEITA. As the result of performing correlation, the D.Flicker has higher correlation coefficient (r) than JEITA (r(JEITA)=0.691, r(D.Flicker)= 0.923).

Implication of VRR flicker detection experiments

The results of the two subjective tests show the index using IRF based on the time domain analysis can well explain the users' experience of VRR flicker. Comparing the VRR situations between the VESA VRR flicker test and the controlled experiment of the abrupt switch between two refresh rates, the VESA test includes the continuous changes in refresh rates: zigzag and sinewave scenario. For the JEITA, the correlation coefficient including the zigzag and sinewave scenarios was significant lower than the situation of abrupt switching between two refresh rates. This is because JEITA only uses the power intensity of main frequency from the waveform, while it is difficult to extract the main frequency in the VRR waveforms when the refresh rates change gradually. On the other hand, D.Flicker's correlation coefficient seem to maintain a similar level since the IRF is a filter that can interpret the time interval and brightness difference between successively presented stimuli.

Conclusion

As the user experiences with VRR flicker increases, the research has been conducted recently to accurately interpret VRR flicker. Because the VRR waveforms appears aperiodically, it is required to interpret information of all frequencies to which hat human can response. In addition, since VRR flicker occurs unpredictably, it is also necessary to capture the onset time occurring luminance changes in the VRR waveforms. In the traditional approach, flicker is mainly analyzed in the frequency domain. That is, a fast Fourier Transform is performed and the filters one the sensitivities of the temporal frequency are applied. However, the result of testing the visual causality showed that the frequency domain did not capture the time when the luminance changes appear. Therefore, we proposed D.Flicker, a new VRR flicker index, using the IRF based on the time domain analysis. As a results, the D.Flicker method can preserve visual causality and explain the various VRR scenarios.

However, there are some supplements to D.Flicker. The perceptual congruence between user experience and the values of D.Flicker varies depending on what TSF model is converted to IRF. It is required to further develop the accurate TCSF model or IRF model that well describe the brightness and size effect on flicker perception. In addition, since the values of D. flicker is small, it seems insufficient to grasp the difference in the amount of VRR flicker. The formula needs to be supplemented so that the index value can be read intuitively.

Acknowledgments

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