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Effect of brightness and size on display flicker perception: Comparison with Flicker Indices

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Abstract

Critical Flicker-Fusion Frequency (CFF) refer to the frequency at which people see a steady, single intensity of light when when given alternating bright and dark light. While most displays have been developed with a refresh rate of 60Hz, revealed as the frequency above CFF, the state-of-the-art displays with the technology called VRR(Variable Refresh Rate) are emerging, which supporting the various frequency from the lower frequency to the higher frequency than CFF. In addition, dispays have became bigger and brighter. Since it was revealed that brightness and size affect flicker perception, it is needed to inverstigate how these two factors affect flicker perception on displays with the lower refresh rate than CFF. Simulating the images with 30Hz, we observed the effect of brightness and size on display flicker perception. Additionally, we compared the result with various indices, representing the amount of flickering. As the result, participants perceived flicker stronger as luminance of stimuli increased and as the size of stimuli increased. However, none of flicker indices reflected these tendencies such as JEITA, Flicker Visibility, and Flicker Modulation Amplude. Since displayes makers generally use the flicker indices for representing the amount of flicker, there indices needs to be supplemented to include the effects of brightness and size.

Introduction

Most displays have a refresh rate of 60Hz. This means that the display cycles on and off the screen 60 times per second. This time (1/60 second) is known to be shorter than the time unit in which the viewer can perceive a temporal change of light [1]. In this way, it is called the critical fusion frequency (CFF) that the frequency in which the change in intensity of light over time is not detected. Genenally, CFF is known to be 50 to 60 Hz [1]. Looking at a display with a refresh rate lower than 60Hz, the viewers may detect a change in intensity of light over time. Recently, the need for researches on display flicker perception with a low refresh rate has been raised again. There are two reasons: one is that latest monitor s have properties beyond the range of stimuli in the previous studies, the other is to apply the new technology of the variable refresh rate (VRR).

Regarding the displays' characteristics to affect on display flicker perception, the brightness and size can be chosen as main factors. For brightness, it is revealed that brightness of stimulus can affect flicker perception [2,3]. The brighter the stimulus, the more perceptible the flicker [2-5]. Most experimental appatus on display flicker perception had around 100cd/m^2 in the previous researches, while the state-of-the-art monitor has beyond 400cd/m^2. For size, the bigger the stimulus, more visible the flicker [6,7]. Although the range of displays' size was not different from that of stimuli in the previous studies, it is required for maching the result of human perception with the flicker indices that represent the amount of display flicker perception. It is because that the makers generally use these indices as the criterion for verifying their products without flickering.

In the international standards, there are some indices which represent the amount of flicker on displays: JEITA and Flicker Visibility (F.V.) from IDMS (Information Display Measurement Standard) [8], released by ICDM (International Committee for Display Metrology), and Flicker Modulation Amplitude (FMA) from IEC (International Elecrotechnical Commission) [9]. Although the formulas for the three indices are different, all indices use the weighing functions which reflect the human perception of temporal characteristics. However, none of the indices use a weighting function which takes brightness and size into account. F.V. uses the weighting function based on a temporal contrast sensitivity function (tCSF) of de Lange's study [2] and FMA does on Kelly's tCSF [3]. The former had brightness around 60cd/m^2 [4] wheares the latter did more than 100cd/m^2. However, FMA uses only one brightness condition in the tCSF curve. Moreoverall, the gaps between brightness conditions on Kelly's tCSF was wide, so it is difficult to estimate the tCSF curve at a specific brightness condition. Watson and Ahumada [4] revealed that contrast sensitivity on tCSF increased as the stimulus had high luminances beyond 100cd/m^2 through the modeling between CFF and brightness (retinal illuminance (Tr: Troland)) [10]. However, they did not match their conclusion with the result of psychophysics experiment, it is required to connect to the actual visibility. Moreover, although the stimulus size is also a main factor to affect flicker perception, the flicker indices of displays are not reflect it.

On the other hands, recent newest monitors have introduced the technology of VRR which has wide range of a refreah rate including both lower and higher refresh rate than the conventional refresh rate of 60Hz. This technology has been developed in order to adopt a high refresh rate for enhancing the image quality of moving contents. If users choose it on their monitors, however, the electric power consumption will increase. In order to decrease the power consumption of displays with a high refresh rate, the monitors automatically has a lower refresh rate than 60Hz when users see static images or moving images with low speed such as reading the contents and seeing photos. This technology is called as VRR or adaptive refresh rate [11,12]. If VRR is applied to the monitors, the power consumption decreases when the monitors presents images with a lower refresh rate than 60Hz, but users are more likey to detect flicker. Therefore, the study for flicker on monitors with high brightness and low frequency is required.

Considering the direction of recent development on displays with a high brightness and VRR, we will study display flicker perception at a refresh rate of 30Hz, lower than the conventional refresh rate of 60Hz. Before conducting the experiments, we analyze the flicker indices which represents the amout of flicker. It is important to reveal the congruence between these indices and the results of psychophysics experments. In this study, the independent variables are brightness and size, as recent monitors become brighter and larger. We will conduct the two psychophysics experiment of brightness and size on flicker perception and will compare the results of two experiments and the flicker indices. In conclusion, we will suggest the guide of choosing flcker indices which shows the flicker perception on displays.

The Flicker Indeices

In the international standard, there are three indices that express the flicker perception on displays: JEITA and F.V. and FMA. Fig.1 shows the structures for calculating flicker indices. The first step (block1) is acquiring the waveform of light modulation, and then in the next step, the power spectrum is acquired (block2) by performing the Fast Fourier Transform (FFT). The third step is to calculate the convolution of the power value from FFT and the weighting function which reflects human perception on flicker (block3). Although three indices use different weighting functions, the steps from 1 to 3 are same.

The flicker indices can be divided to two groups depending on whether there is or not the process of converting to the perceived luminance (Fig.1: block 4). For FMA, through the inverted FFT, the waveform of the perceived luminance is acquired, while for JEITA and F.V. this step is passed. Finally, according to each formula, the flicker index is calculated.

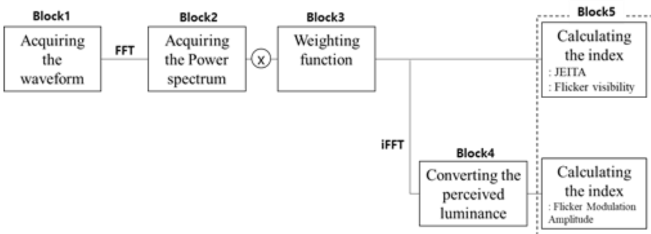

Figure 1. The structures for calculating flicker indices

The JEITA's weight function considers only the the frequency (temporal characteristic) as one factor, while the others also does the contrast (spatial characteristic) as well as the frequency (temporal). However, all three weighing functions do not reflect the brightness of stimulus. Although, in the Kelly's original study [3], the tCSF curves varied with stimulus brightness (unit: Troland), the IEC standard selected tCSF for one brightness condition (77Tr). Moreoverall, the stimulus size was not included in the weighting function as the factor. Therefore, in the next two experiments, we will observe how much there is a discrepancy between the flicker indices and the results of the psychophysics experiment on display flicker perception due to omit the two factors of stimulus brightness and size from flicker indecies.

Experiment 1: Effect of Brightness

Method

In this study, we used a display with the high refresh rate of 240Hz (model: ASUS PG258Q, 24.5-inch). By controlling luminances of eight frames of 240Hz to mimic the waveforms of 30Hz, participants were able to perceive the eight frames of 240Hz as the one frame of 30Hz. Using Matlab, we made the flicker stimuli as the moving image format, presenting bright and dark achromatic images on the monitor screen temporally.

Test stimuli were six with several visibility of flicker. The two type of test stimuli were simulated: the one was LD (Luminance Difference) type and the other duty type (Fig.2). The LD type had a waveform that reduced the brightness within one frame of 30Hz [13]. We controlled the amount of flicker in 30Hz-LD type stimulus by the LD ratio, which meant the percentage of the luminance between the 1st frame and the 8th frame of 240Hz. The value of 100 in LD ratio means that the luminance of the 1st frame is same to that of the 8th frame of 240Hz. As lower the LD ratio, the more flicker perception. Three stimuli with 30Hz-LD type was used in the experiment. The second type was duty type. It was simulated as a square waveform with duty cycles called PWM (Pulse-With Modulation). The stimuli with 0.5 of the duty ratio, in which the half of 1 frame was on and the other half was off, were simulated named as "duty50" stimulus as the percentage. Last, one control stumulus was made with 60Hz-LD type.

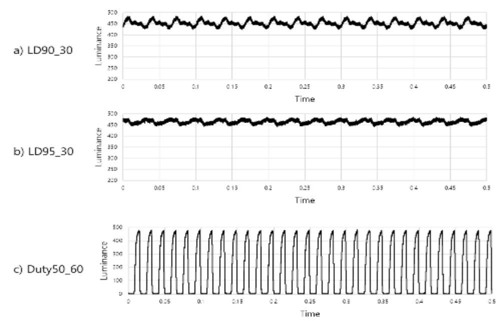

Figure 2. Two different waveform, LD-type (a,b) and Duty-type(c)

To investigate the pure effect of brightness on display flicker perception, the stimuli shoud maintain the same shape of the waveform despite of the brightness. For keeping the same shape, we adjusted luminances of stimuli using an option in the brightness settings of monitor (three levels of the Monitor brightness). Table 1 shows luminance of each stimulus at each brightness level of the monitor setting. Since previous studies revealed the effect of brightness in the range of less than 100cd/m^2, we focused the range of more than 100cd/m^2. The Duty type had lower luminance than the LD type due to being off-period within 1 frame. Verifying the maintaining same shape, we normalized the measured waveform of stimuli at each brightness level of the monitor.

Table 1. The characteristics of six test stimuli and one reference stimulus.

Stimulus		Hz	Luminance(cd/m^2) at each monitor brightness level			LD ratio (%)
			100	50	0	
Test	LD90_30	30	443	279	106	90
	LD 94_30	30	453	285	108	94
	LD 97_30	30	465	293	111	97
	LD 92_60	60	443	279	106	92
	Duty50_60	60	163	102	39	0
	Duty50_120	120	106	66	25	0
Ref.	ES88_36	36	370			88

Reference stimulus was used to set criteria for the amount of flicker when participants evaulated the flicker scores of the six test stimuli. To avoid adaption to flickering with a specific frequency [1], we made a reference stimulus with a different frequency from test stimuli's frequency. Reference was divided into two areas: on the left region, the image without flicker was presented and on the right, the image with flicker was. No flicker images was set as the score of 0 and flicker image of the reference as the score of 5. In order to block the ceiling effect and the floor effect, reference stimulus had an intermediate level of flicker among six test stimuli. To compare all stimuli and to verify the amount of flicker, we measured two flicker indices, JEITA and Flicker Visibility. Reference stimulus was presented on another screen of a laptop (model: MSI GS75 Stealth 8SF, 144Hz, 17.3-inch).

The task of participants was to answer the flicker score of six test stimuli comparing the flicker of the reference image. We explained that the reference image without flicker was set as the score of 0, the image with flicker was as the score of 5. Participants were asked to rate less than the 5-score to the the test stimulus when they perceived flicker of the test stimulus stronger than that of reference, while to rate more than the 5 when they perceived flicker of the test stimulus weaker than that of reference. Threr was no limt of upper score.

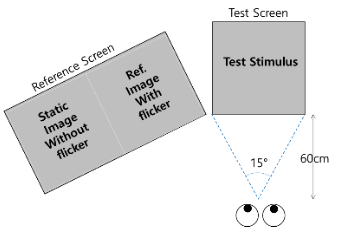

Figure 3.The picture of experimental setup.

After listening to the explanation of the experiment, partipants sat in front of the monitor where the test stimuli were presented. The monitor where the reference appeared was located beside the monitor of the test stimulus. Participants had to turn their chairs slightly to see the reference stimulus from the front (Fig. 3). The vieweing distance was 60cm (the size of the test and reference stimumlus: visual angle 15°).

Participants evaluated the flicker scores of test stimulus three times. The presenting order of test stimuli and the order of the monitor brightness were randomized. For blocking adaption to flickering with a specific frequency of the reference stimulus [1], we turned off the reference stimulus before starting the experiment. Before each repeatation, we presented the reference to the participants and they were also able to ask seeing the reference stimulus if they wanted. The experiment was conducted in the dark room. Total fourteen subjects with normal color vision participated the flicker experiment (Gender: 4(Male) and 10(Female), the average age: 33.85).

Result of the experiment on brightness

For analyzing relationship between the amount of flicker and the brightnee of stimulus, the linear regression was performed as a independent variable was the brightness and a dependent variable was the flicker scores utilizing the statistical program of Minitab. The reason for choosing analysis of simple linear regression was that CFF, which directly associated with detecting flicker, increased linearly as the logarithmic value of the stimulus brightness increased [2-4]. As the result, the logarithmic value of luminance on each test stimulus was significantly predicted the amount of flicker. The overall regression was statistically significant (R^2(adj.) = 54.2%, F(6, 738) = 149.9, p < 0.001). It is found that the brightness of stimulus significantly predicted the amount of flicker (β = 0.790, p < 0.001). The brighter the stimulus, the stronger participants perceived the flicker.

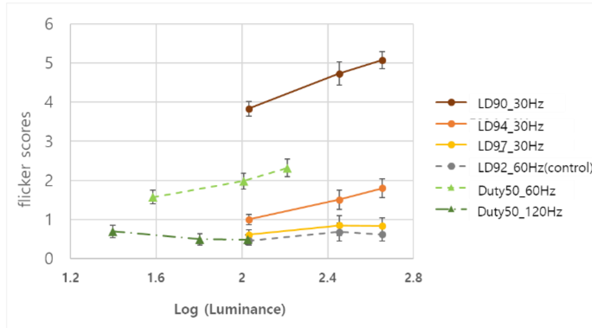

Figure 4. The result of the experiment on brightness

In order to observe the consistency between the flicker indices in the international standard and the result of the experiment, the correlation coefficient was computed using Minitab. First, through an oscilloscope and a RD80S, we acquired the waveforms of six stimuli at each monitor brightness level. Next, we calculated three flicker indices and then performed a Pearson correlation analysis to assess the relationship among them. As the result, there were a correlation between the indices and the result of flicker perception (JEITA: r = .427; F. V.: r = .661; FMA: r =-.155, p < .001)) since none of three indices consider the effect of brightness (Fig. 5&6). F.V. seemed to refliect the brightness effect, but it was presumed to be due to the noise of measurement at low brightness [14].

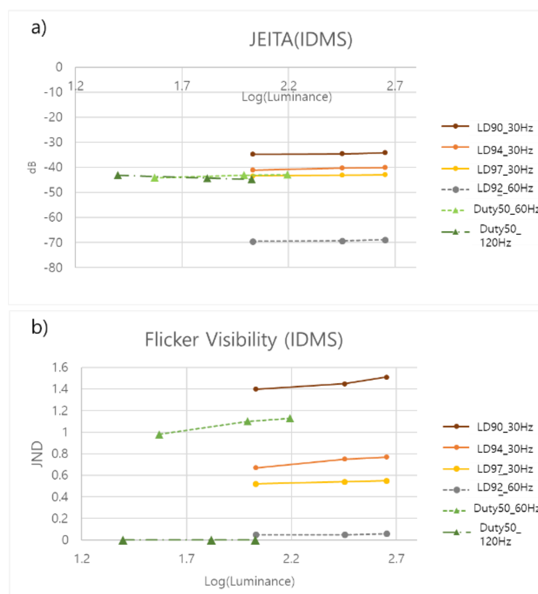

Figure 5. Two flicker indices, JEITA and Flicker Visibility(F.V.), defined by IDMS on each test stimuli

However, only FMA showed the negative correlation with the result of flicker perception. The brighter the stimulus, the smaller the value of FMA (Fig. 6). This opposite tendency seemed to be due to the value of perceived luminance modulation (PLmax- PLmin) divided by the average luminance in the formula of FMA. If the brightness increases, the value of FMA will decrease despite the same luminance modulation.

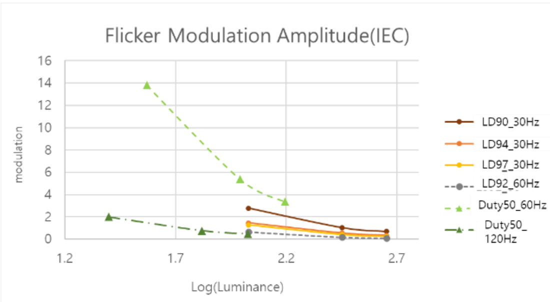

Figure 6. The flicker value calculated by FMA on each test stimuli

Interpreting the relationship between the amount of flicker on each stimulus and three indices, the "duty50" stimulus with 60Hz showed most inconsistent in the three indices. The index of F.V. had most similar to the result of flicker perception. The others did not reflect the perceived flicker of duty50-60Hz-stimulus. In the case of JEITA, duty50-60Hz- and duty50-120Hz-stimulus had similar flicker value because the weighting of stimuli above 60Hz is the same. In the case of FMA, duty50-60Hz-stimulus seemed to be oversestimated, even ignoring the oppiste tendency in the brightness of stimulus.

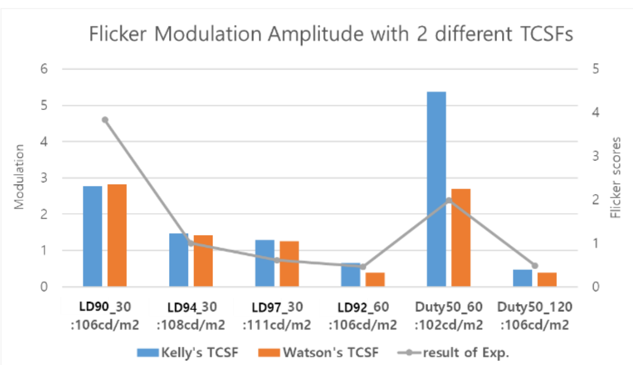

Figure 7. Comparing the two values of FMA: the blue was calculated by original TCSF(Kelly's) and the orange was by Watson's TCSF, which defined in Flicker Visibility (IDMS).

For finding the reason of FMA's overestimatation, we calculated the FMA using Watson's TCSF of F.V. instead of Kelly's TCSF of FMA since the index of F.V., calculated from Watson's TCSF, had good consistency with the result of the experiment. Comparing two TCSFs, Watson's TCSF had lower contrast sensitivity of 60Hz than Kelly's (contrast sensitivity at 60Hz: 0.78(Watson), 1.23(Kelly)). Our assumption was that FMA's overestimation might result from the high contrast sensitivity of 60Hz. As the value of FMA decreases with increasing luminance, we analyzed the stimuli of only one brightness condition with similar luminance of 100cd/m^2. As the result, the value of FMA calculated by Watson's TCSF became lower than the original value of FMA, calculated by Kelly's TCSF. This result was more similar to the flicker scores of the brightness experiment (Fig.7). When the stimuli were ranked based on the severity of flicker, the values of FMA derived from Watson's TCS were more similar to the flicker scores in the experimental result.

In conclusion, the flicker increased linearly as the logarithm value of the stimulus luminance. However, none of three flicker indices reflect this tendency. Therefore, the weighting functions should be supplemented in order to represent human perception on flicker.

Experiment 2: Effect of size

Method

Same to the experiment of brightness, we mimicked a stimulus with 30Hz via a 240Hz-LCD monitor. We used total five test stimuli. Of these, three stimuli of "LD90_30", "LD94_30", and "LD_30" were same in the exp. 1. New two stimuli were made: LD62 with 60Hz and LD0 with 60Hz. Differently in the exp. 1, the stimulus with 120Hz was excluded as participant were not able to detect flicker in the experiment 1 and as the wighting functions of three flicker indices do not consider at 120Hz. Instead of duty type, we simulated a similar waveform of "LD0" (Fig. 8). Since a stimulus with "duty50" had lower luminance than other stimuli, we tried to make a stimulus which had a similar waveform to duty type and had a similar luminance with other stimuli. Two stimuli of "Duty50" and "LD0" were same for having the luminance modulation between 255 gray and 0 gray, but the period of 255 gray was different..

The same reference stimulus in the experiment 1 was used except brightness. Not only for maintaining the waveform, but also for matching the brightness similarly with test stimuli, the luminance of the reference (124cd/m^2) was adjusted by controlling the monitor brightness setting.

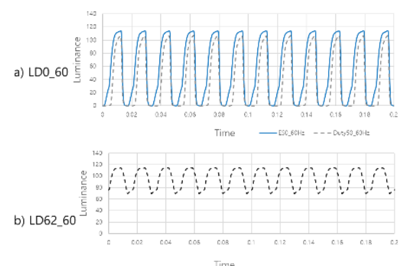

Figure 8. The waveforme of two new stimuli in experiment 2.

The level of size on test stimuli was 5: visual angle 2°, 5°, 10°, 20°, and 30°, while the size of the reference was set as one condition,visual angle 15°. The location where the screen with the test stimuli and that with the reference were placed was same in the experiment 1 except the viewing distance from the screens to the participants of 40cm. All procedure was same in the experiment 1. The task of the participants was to rate the flicker scores of five test stimuli three times. The order of presenting stimulus and that of the size level were randomized to avoid the order effect. The experiment was conducted in the dark room.

Result of the experiment on size

For analyzing relationship between the degree of flicker and the size of stimulus, a repeated Analysis of Variance (ANOVA) was performed as a independent variable was the size and a dependent variable was the flicker scores utilizing the statistical program of Minitab. As the result, there was a statistically significant difference in the flicker scores between at leat two groups ($F(4, 1012) = 129.41$, $p < 0.001$). Fig. 9 shows the average flicker scores of each test stimuli.

Although the flicker scores increased depending on increasing size, it tended to be logharithm-relation rather than linear.

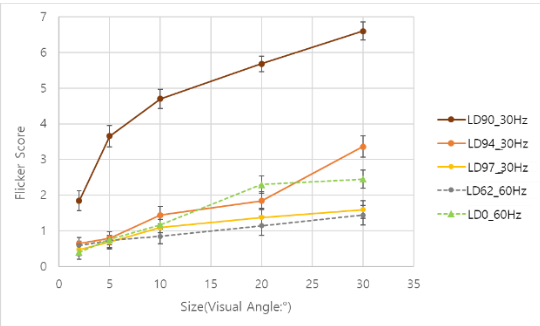

Figure 9. The result of the size experiment

In order to explore the consistency between the flicker indices in the international standard and the result of the size experiment, the correlation coefficient was computed using Minitab. As the result, there were a significant correlation between two indices and the result of flicker perception (JEITA: $r = .456$; F. V.: $r = .573$, $p < .001$). However, FMA was not statistically significant ($r = -0.012$, $p = 0.698$). Nontheless, none of all indices reflected the size effect because the weighting functions did not include stimululs size as one factor.

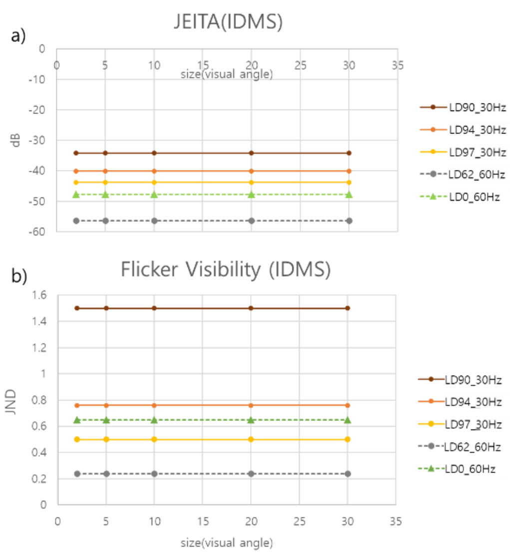

Figure 10. The flicker indices of each stimulus depending on the size. a) JEITA, b) Flicker Visibility

Figure 10 and 11 shows the three indices of all test stimuli depending on the stimulus size. The different correlation coefficients of three indices seemed to be related with how well the index reflected the amount of flicker in each stimulus. Since JEITA calculated the similar amount on two stimuli with 60Hz, it is required considering contrast as one factor. Namely, using tCSF as a weighting function seems to be more adequate for the flicker index. On the other hands, FMA seemed to overestimate the degree of flicker on “LD0-60”. It was same to the result in the brightness experiment. The weighting function in FMA may need to adjust an weight corresponding to 60Hz.

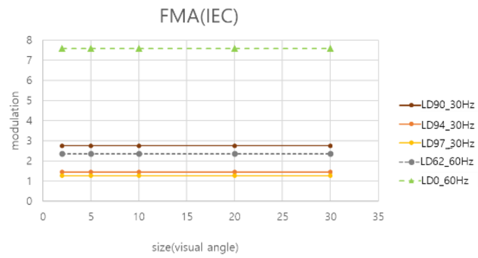

Figure 11. The flicker values of FMA depending on stimulus size

In conclusion, however, none of all indices reflected this tendency. Therefore, the weighting functions should be supplemented considering the size as one factor.

Discussion

From the results of two experiments, it was revealed that the brightness and the size of stimulus was related with display flicker perception. However, the flicker indices, which defined by the international standards and used as the amount of display flicker, do not consider these effects. Therefore, the brightness and the size should be included to the weightng function as main factors. It is because the weighting function directly detenmines the value of the flicker index.

For brightness, although Kelly’s study [3] on TCSF already included the brightness as the main factor, IEC chose the only one condition of brightness (77 troland). Troland, the retinal illuminance, can not direcly be converted into the unit of luminance, but it can be calculated using an estimated pupil size. Based on the previous studies [15-17], 77tr may correspond to luminance condition of 5~10cd/m2. As Kelly included the condition of 9300tr on his TCSF (Fig.12), it is needed to consider the tCSFs of various bright conditions on IEC standard.

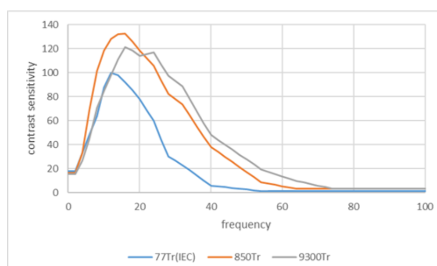

Figure 12. Three Kelly’s tCSFs depending on the brightness

In order to verify the hypothesis that the consistency between the flicker index and the human perception on flicker if the index is calculate choosing the tCSFs corresponding to the stimulus luminance, we compared the correlation coefficients between the participants’ flicker scores in the brightness experiment and two FMA indices: one was calculated from the tCSF of 77Tr, another from that of 850Tr. In the formular of FMA, the amplitude of perceived luminance (a numerator) was divided by the average luminance (a denominator). If two stimuli had different average luminance, FMA was calculated differenctly despite of the same amplidute, so we chose only one brightness condition of around 100cd/m^2. As the result of performing the correlation anaylsis using Minitab, FMA from tCSF of 850Tr had a higher positive relation with the flicker scores in the human experiment than that from 77Tr, which is defined as the weighting function in the IEC (Table 2). Therefore, the weighting function should be selected corresponding the stimulus brightness.

Table 2. The correlation coefficient (r) between the flicker indices and the participants' flicker scores (in exp1)

	FMA(77Tr)	FMA(850Tr)
r	-0.121	0.422
p-value	0.056 (n.s.)	<0.001

For size, the difference between Flicker Visibility and FMA may result from the different stimulus size of two TCSF, Kelly's and Watson's. Kelly used the stimulus with a 50-visual-degree, while de Lange, whose study was based on the Watson's TCSF, measured TCSF with a 2-visual-degree test stimulus. We assumed that a higher weight on 60Hz of FAM also came from a bigger size than that of Flicker visibitility. Therefore, for including the size effect, an united tCSF should be developed.

Barten [19,20] tried to develop an united tCSF model, including the brightness and the size as the main factors, through metadata analysis. While his modeling is more suitable than a tCSF with one brightness or one size condition, the source researches, from which metadata analysis was conducted, did not cover the brightness and the size range of state-of-the-art displays. In the further study, therefore, an united tCSF model should be deried from the study on the fundamental tCSF including the wide ranges of the brightness and the size. After verifying the consistency between the flicker index from this model and human perception on display flicker, it is needed to apply a measuring instrument.

Conclusion

Considering the characteristics of the newest display, being brighter and larger and applying VRR technology, we investigated the brightness and the size effect on display flicker perception. Flicker scores in human experiments increased as luminance or size of stimulus increased. Although none of flicker indices take into account the effects of brightnes and size, we propose that the weighting function should be selected depending on the brightness and size of the stimulus in order to match the users' flicker perception with flicker indices.

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