Measurement and Modeling of Viewing-Condition-Dependent Spatio-Velocity Contrast Sensitivity Function

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Abstract

In this paper, spatio-velocity contrast sensitivity functions (SV-CSF) were measured by changing stimuli sizes and viewing distances, and a viewing-condition-dependent model of the SV-CSF are build based on these measured data. The viewing-condition-dependent SV-CSF model is particularly required to evaluate and improve moving image quality on large-sized flat panel displays. In the measurements, observers' thresholds of contrast sensitivities were obtained by subjective evaluations by 10 observers. From the experimental results, we found that the peak values of contrast sensitivities to stationary stimuli are varied with relative viewing distances. The relative viewing distance is a normalized distance by the size of display device. The highest peak of contrast sensitivities is observed at the viewing distance of three times size of display device. Based on these measured data, the viewing-condition-dependency of the SV-CSF is modeled as a concave function of the relative viewing distance.

Introduction

Recently, flat panel displays (FPDs) such as liquid crystal displays (LCDs), plasma display panels (PDPs) and rear-projection televisions become significantly larger and thinner according to the development of the technology, and they have been widely used instead of traditional cathode-ray tube (CRT). As these FPDs become popular, it became the important works to compare image quality such as gonio-photometric characteristics, sharpness, color reproduction, tone reproduction and noise characteristics of those displays. In particular, the FPD devices are known to have temporal artifacts called 'motion blur' due to hold-type displaying method [1] [2]. Therefore, a lot of evaluation and improvement methods are proposed to reduce the motion blur [3-6]. Moving picture response time (MPRT) measurement method is well known as motion blur evaluation of FPDs [7] [8] and standardized in VESA (Video Electronics Standard Association) [9]. In the MPRT measurement method, it is required to capture the horizontally moving blurred edge images by using pursuit camera, and the MPRT is calculated from the captured images. Although the MPRT is mainly used as motion blur criterion in FPD's industry, a previous research has reported that MPRT isn't well correlated with human perception [10]. To build more correlated criterion with human perception, it is necessary to combine the MPRT method with human visual characteristic during the eye movement. In 2006, Oka et al. proposed novel motion blur criterion by applying contrast sensitivity function (CSF) of human visual system to the captured blur images [11]. For evaluating the motion blur, they used spatial CSF filter. However we consider that both spatial and temporal CSF should be used to evaluate motion image quality during the eye movement.

In the field of vision science, a lot of CSF models have been proposed, and used to evaluate the image quality in the practical applications. A spatio-temporal CSF (ST-CSF) or spatio-velocity CSF (SV-CSF) is required for evaluating motion blur. In the previous research, Kelly built a ST-CSF model for exploring the influence of moving stimuli on contrast sensitivity. He investigated contrast sensitivity as a function of velocity across the retina. Kelly modulated image velocity across the retina using an unique retinal stabilized instrument and could keep the stimulus stationary on the observer's retina. He measured contrast sensitivities by using a variety of spatial frequencies with constant velocity and built 2D CSF model. In 1998, Dally revised Kelly's model by incorporating smooth eye movement characteristics into the models [13]. He proposed the SV-CSF model with eye movement based on the experimental data of some previous works. For validating the Daly's model, Laird et al. explored contrast sensitivity with retinal velocity [14]. In order to estimate motion blur on FPDs, it is useful to apply the SV-CSF model with eye movement to the captured moving edge image. However, the conventional models have been proposed based on not various detailed experimental results, but the data of previous works and brief experiments. For analyzing perceived motion blur on FPDs, it is required to measure the CSF with eye movement using the stimuli with various spatial frequencies and velocities, and model the CSF from the detailed experimental data.

On the other hand, in 2005, Johnson suggested human perception of spatial frequency is influenced by viewing-distance or stimuli size [15]. As described above, recent FPDs have significantly large size and the viewing-distance also change with the emergence of large-sized FPD's. In discussing perceived motion blur of recent FPDs, it is also required to examine the relationship among the CSF, viewing-distance and stimuli size.

In this research, we measured CSF by using moving stimuli under the experimental conditions with various viewing distance and stimuli size. In the experiments, for clarifying the influence of stimuli size in human perception, we don't only change size of stimuli images but also size of devices. Moreover, we propose a new SV-CSF model by modifying the conventional models and combining the influences of size and distance with the modified model.

Measurements of SV-CSF

In the measurement experiments, contrast sensitivity were measured under two different conditions as shown in Fig. 1 for exploring influence of devices size and displayed image size on

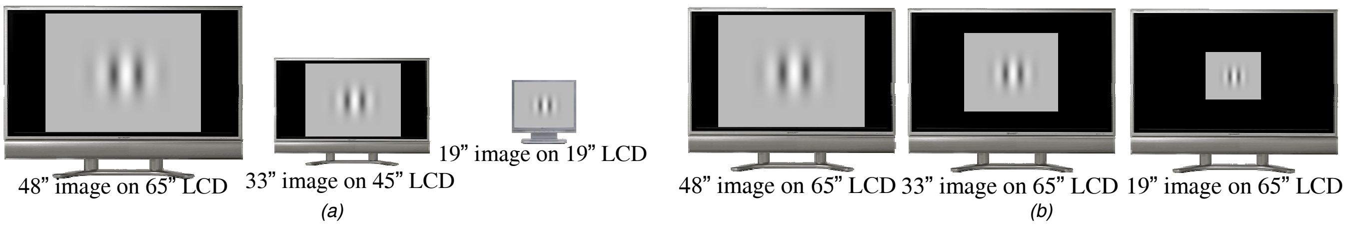


Figure 1. *Two kinds of experiment for measuring SV-CSF (a) Condition 1 : stimuli images on three LCDs (b) Condition 2 : stimuli images on 65”LCD*

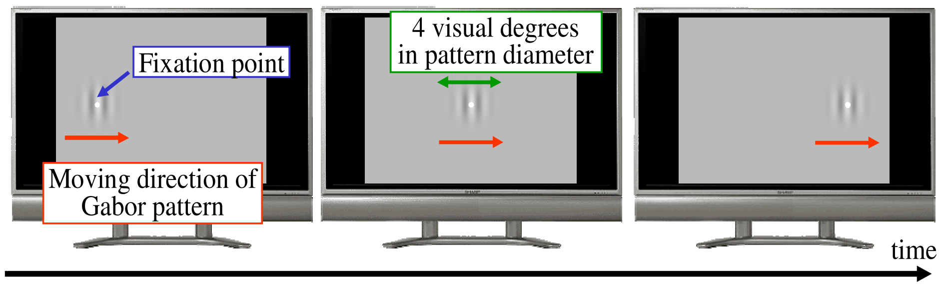


Figure 2. *Displayed Gabor pattern*

human visual system. The first condition consisted of three display devices (19, 45 and 65”). The stimuli images with 1280 × 1024 pixels and sizes of 19, 33 and 48 inches were displayed on each device. In the other condition, three kinds of the stimuli image are displayed by using only the 65’’ LCD. Actually, the conditions of 48” image on 65” LCD in the both experiments as shown in Fig. 1 were explored only once because the experiments consist of same condition.

Table 1 shows other viewing conditions to measure contrast sensitivities. The conditions were same under the two experiments shown in Fig. 1. Gabor patterns of 4 visual degrees in diameter were used as the stimuli and the patterns moved from left to right on the displays as shown Fig. 2. The average luminance of stimuli is 100 cd/m^2. In this experiment, an up-and-down method was used for obtaining the thresholds of contrast sensitivities. ten observers observed the stimuli images with various contrasts and judged if displayed spatial frequency was viewable or not. The observers were also instructed to fix their gaze on a fixation point in the stimuli. The viewing distances are 900, 1700 and 2400 mm which are decided based on three times the each LCD’s screen height because three times screen height (3H) is recommended as optimal viewing distance for watching displays [16][17]. The spatial frequencies were 8 steps from 1 to 15 cycle-per-degree (cpd) and the velocities were 3 steps (0, 10, 15 degree-per-second (dps) on the observer’s retina) that were decided based on the previous report which surveys viewing conditions of household TVs [18]. Figure 3 shows an example of the experiment.

Table 1. Experimental viewing conditions

Stimuli	Gabor pattern
Viewing distance	900, 1700, 2400 [mm]
Average luminance	100 [cd/m^2]
Spatial frequency	1, 3, 5, 7, 9, 11, 13 15 [cpd]
Velocity	0, 10, 20 [dps]
Room condition	Dark room
Measurement method	Up-and-down method
Number of observers	10 observers in each condition

Notation: In the condition of 900mm with 45” and 65” LCDs, the displayed spatial frequencies are different from above values because of the pixel pitch.
45 inch: 7 steps (1, 3, 5 ,6, 7.5, 10 and 15 cpd)
65 inch: 5 steps (1, 3, 5 ,7 and 10.5 cpd)

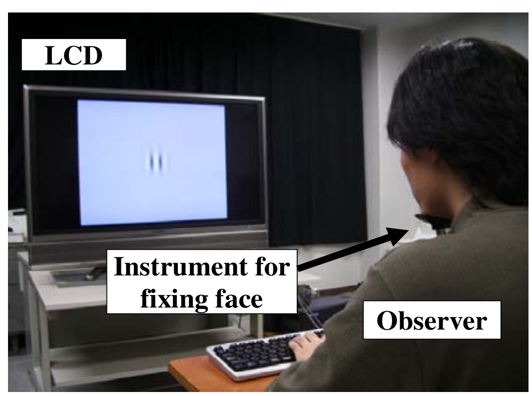
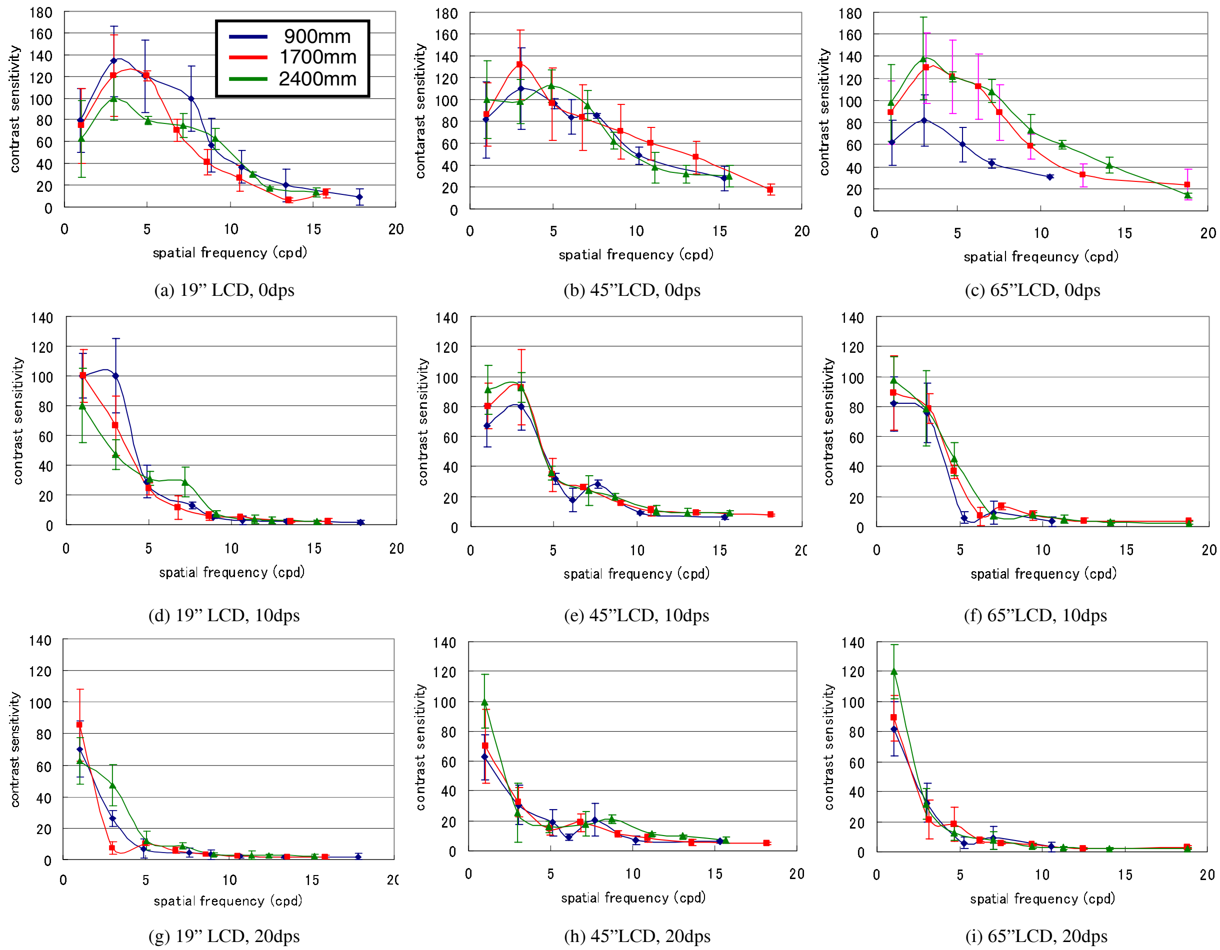


Figure 3. *An example of the experiment (45” LCD, 1700mm viewing distance)*

Results and Discussion

Figure 4 shows the measurement results of CSF for the three LCDs in different viewing conditions. In general, visual system of spatial frequency has band-pass characteristic with the peak from 3 to 7 cpd. As the velocity of stimulus increase, the peak becomes close to lower frequency. In our experiments, the results denote the similar tendency as conventional studies. On the other hand, the peaks of contrast sensitivities to stationary stimuli as shown in Fig.4(a)~(c) are the highest under the conditions with 19” LCD from 900mm, 45” LCD from 1700mm and 65” LCD from 2400mm. In other words, the highest peaks are under the conditions with relative viewing distances of 3H. The figures also indicate that the contrast sensitivities have similar values in the distances between 3H ± 800mm. However, the values significantly

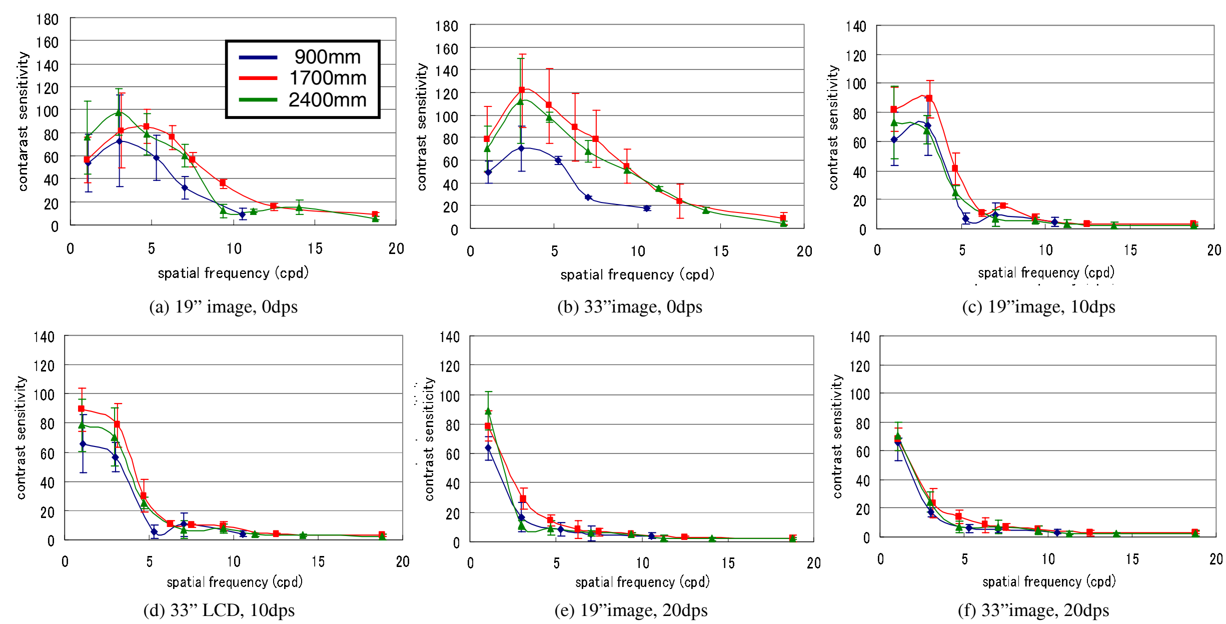


(a) 19” LCD, 0dps (b) 45”LCD, 0dps (c) 65”LCD, 0dps

(d) 19” LCD, 10dps (e) 45”LCD, 10dps (f) 65”LCD, 10dps

(g) 19” LCD, 20dps (h) 45”LCD, 20dps (i) 65”LCD, 20dps

Figure 4. *Results under the condition with stimuli images on three LCDs (Error bar: 95% confidence interval)*



(a) 19” image, 0dps (b) 33”image, 0dps (c) 19”image, 10dps

(d) 33” LCD, 10dps (e) 19”image, 20dps (f) 33”image, 20dps

Figure 5. *Results under the condition with stimuli images on a 65” LCD (Error bar: 95% confidence interval)*

Table 2. The relationship between the maximum contrast sensitivities and each distances and device sizes

	19” LCD	45” LCD	65” LCD
900mm	134 (3H)	110 (1.6H)	82 (1.1H)
1700mm	120 (5.7H)	132 (3H)	129 (2.1H)
2400mm	100 (8H)	112 (4.2H)	138 (3H)

decrease when the relative viewing distances are far from 3H. Table 2 shows the relationship between the maximum contrast sensitivities and each condition. As shown in the table, we can also see the sensitivities decrease according to far relative viewing distances from 3H. In the experiments with moving stimuli, the influence of the relative distance decreases as shown in Fig. 4(d)~(i).

The results in the other conditions are shown in Fig. 5. It is clear that the measured contrast sensitivities have similar band-pass characteristics as the previous results shown in Fig. 4. In these experiments, three sizes of stimuli images are displayed on the 65” LCD. From the results of stationary stimuli, it is found that the peaks in the conditions of 1700 and 2400mm viewing distances are higher than that of 900mm. This means that the relative viewing distance of devices’ size effects on contrast sensitivity more strongly than that of stimuli image’s size. However, as shown in Fig. 5(a), the influence of relative viewing distance depended on the devices’ size decreases in the experiment with 19’’ images. This suggests that human visual system is influenced by not only the relative viewing distances of device’s size but also that of image’s size. In contrast, it is also noted that the influence of relative viewing distances reduces according to the increase of stimuli velocity.

From the both experiments, we can summarize that the peaks of contrast sensitivities with stationary stimuli is around 3 cpd and that of moving stimuli is around 1 cpd and the tendency are similar to traditional SV-CSF model with band-pass characteristics. Moreover the peaks of contrast sensitivities are the highest under the experimental condition with around 3H of the devices’ size. This indicates relative viewing distance influence SV-CSF.

Modeling of SV-CSF

In the procedure for modeling SV-CSF, at first, we build a basic SV-CSF model by modifying the conventional model. Secondly, the viewing-condition-dependency is modeled as a function of relative viewing distance and velocity. Finally, viewing-condition-dependent SV-CSF model is built by the incorporating the function of relative viewing distance into the modified model.

In our experiments, the results are same tendency as the conventional models which shows SV-CSF is represented as band-pass characteristics in spatial frequency and velocity axis [12] [13]. In this research, our basic SV-CSF model consists of the Dlay’s model as following equations.

$$CSF(\rho, v) = k \cdot c_0 \cdot c_1 \cdot c_2 \cdot v \cdot (c_1 \cdot 2\pi\rho)^2 \exp\left(-\frac{c_1 \cdot 4\pi\rho}{\rho_{\max}}\right)$$
$$k = 6.1 + 7.3 \cdot \left|\log(c_2 v / 3)\right|^3 \qquad (1)$$
$$\rho_{\max} = 45.9 / (c_2 v + 2)$$

where ρ is spatial frequency in cpd and v is the velocity in dps. c_0, c_1 and c_2 are parameters of the model that allow fine tuning and are all equal to 1.0 in the Kelly’s model. The term k is primarily responsible for the vertical shift of the sensitivity as a function of velocity, while the term ρ_{max} controls the horizontal shift of the function's peak in spatial frequency domain. In the first procedure for modeling SV-CSF, the used data for model fitting are the experimental results of 3H (19” LCD from 900mm, 45” LCD from 1700mm and 65” LCD from 2400mm) because they have the most significant influence on contrast sensitivities. Figure 6 shows the results of the fitting. These parameters found by optimization are as follows: $c_0 = 1.00$, $c_1 = 0.56$ and $c_2 = 0.48$. From the figure, it is represented that the peak of the model is around 5 dps in velocity domain. In this research, it is suggested that the peaks of contrast sensitivities in velocity axis are around 0 dps. Therefore the model shown in Fig. 6 is shifted along to velocity-axis as follows.

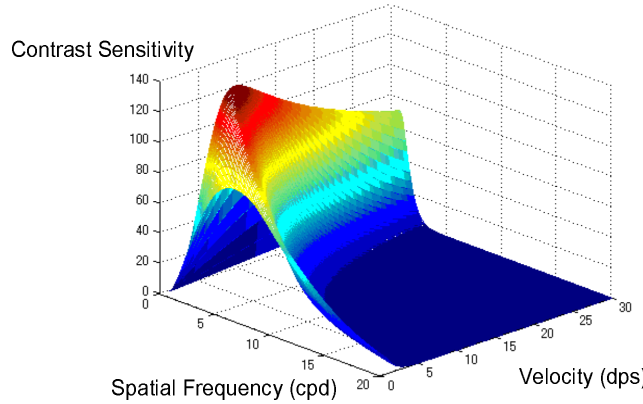


Figure 6. *Result of initial fitting*

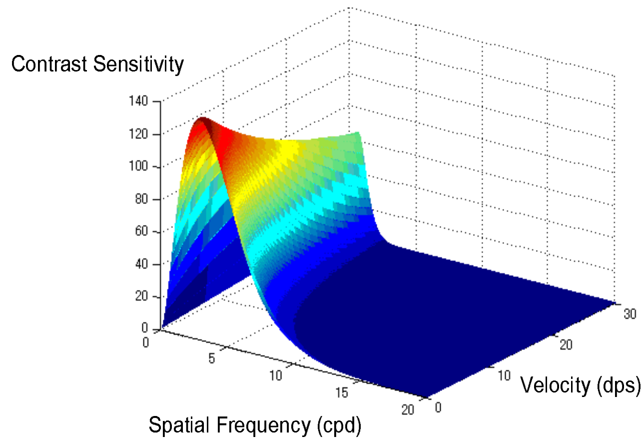


Figure 7. *Shifted SV-CSF model under the condition with relative viewing distance of 3H*

$$CSF_{Shift}(\rho, v) = k \cdot c_0 \cdot c_1 \cdot c_2 \cdot (v + c_v) \cdot (c_1 \cdot 2\pi\rho)^2 \exp\left(-\frac{c_1 \cdot 4\pi\rho}{\rho_{\max}}\right)$$
$$k = 6.1 + 7.3 \cdot \left|\log(c_2 (v + c_v) / 3)\right|^3 \qquad (2)$$
$$\rho_{\max} = 45.9 / (c_2 (v + c_v) + 2)$$

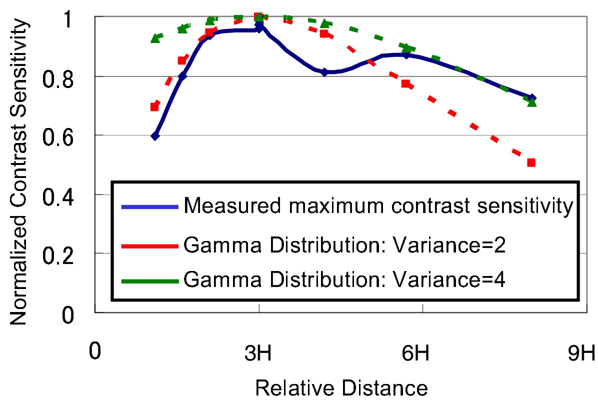


Figure 8. *Relationship between maximum contrast sensitivities and relative viewing distances in experiments with three devices*

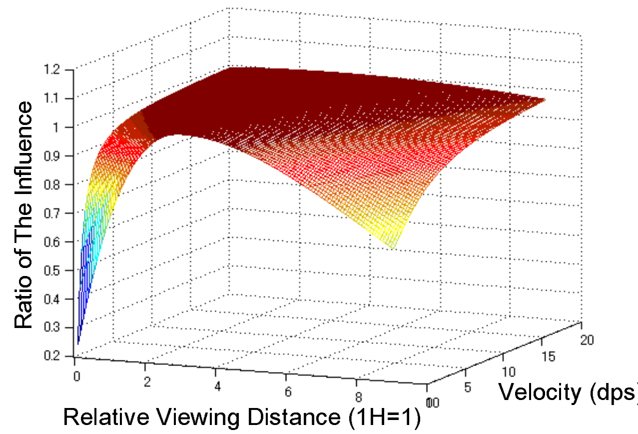


Figure 9. *Influence model as a function of relative viewing distance and velocity*

where c_v controls the shift and are set to 5.1 in our model. Figure 7 represents the shifted SV-CSF model.

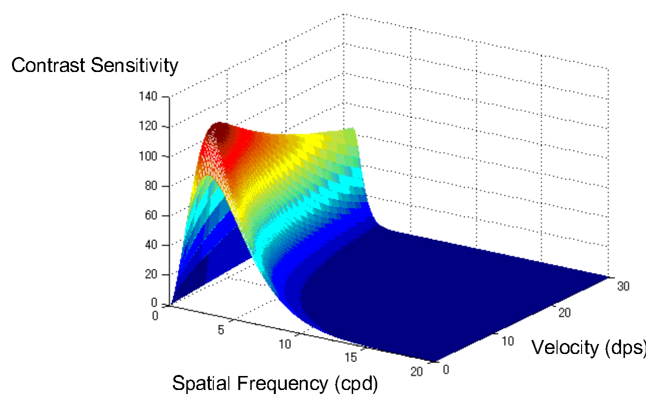
The influence of relative distance is incorporated into the model on the basis of the experimental results and discussion. Figure 8 shows the relationship between the maximum contrast sensitivities to stationary stimuli and the relative distances under the experimental conditions with three LCDs. Assuming that the influence is attributed to gamma distribution, the far side from the optimal distance (3H) has the similar shape of the distribution with high variance. In contrast, near side are approximated by the distribution with low variance. We also assume that the influence of relative viewing distance is constant in spatial frequency domain, but it varies in velocity domain. Based on the observation, we determine the function of viewing conditions as gamma distribution and the influence of relative viewing distance disappear in small steps according to the increase of the velocity in 10 dps. c_{vd} is defined as the viewing-condition-dependent function of relative viewing distance and velocity.

$$
\begin{aligned}
c_{vd}(D,v) &= \frac{x^{(a-1)} \cdot \exp(-x)}{c_{vd\max}} \\
a &= c_{v1} \cdot (v+1)^{c_{v2}} + c_{v3} \\
x &= (D/3) + a - 2 \\
c_{vd\max} &= (a-1)^{(a-1)} \cdot \exp(-(a-1))
\end{aligned}
\qquad (3)
$$

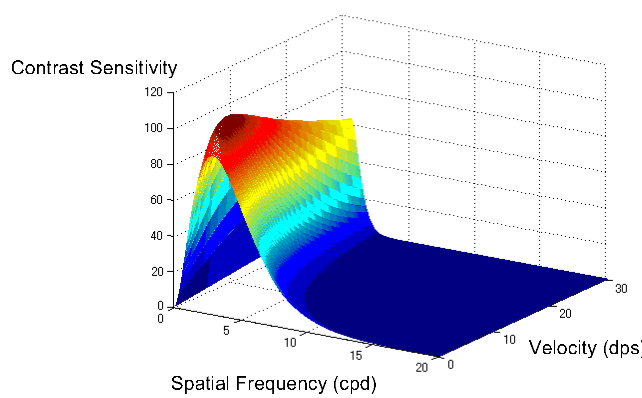
Where D is relative distance from the device, which is defined as screen height H=1. c_{v1}, c_{v2} and c_v3 are parameters for coordinating variances of the distribution. $c_{v3\max}$ is coefficient for normalization. Figure 9 shows the influence model. By optimization, $c_{v1} = 0.5$ and $c_{v2} = 1.5$ are found. Moreover, for building a optimal model, c_{v3} is 3.5 in the far side from the optimal distance 3H and 1.6 in the near side.

In this research, Eqs. (4) is the proposed SV-CSF model with the influence of relative viewing distance and Fig. 10 represents the models which relative distances are 1H and 9H (the model with 3H was shown in Fig. 7).

$$
CSF_{vd}(\rho, v, D) = c_{vd}(D, v) \cdot CSF_{SHIFT}(\rho, v) \qquad (4)
$$



(a)



(b)

Figure 10. *Proposed viewing-condition-dependent SV-CSF(a) relative distance: 1H (b) relative distance: 9H*

Conclusions and Future Work

In this research, viewing-condition-dependent SV-CSF was measured by changing various stimuli sizes and viewing distance. Our results are similar to the conventional SV-CSF models such as

Daly's, which is represented as band-pass characteristics in spatial frequency and velocity axis. However the peaks of contrast sensitivities are the highest under the experimental condition that the relative viewing distances are 3H of the devices' sizes. From these results, we propose a viewing-condition-dependent SV-CSF model that includes the function of relative viewing distance. In the process of the modeling, at first, the conventional models are modified based on our experimental results. Secondly, for incorporating the influence of relative distances into the modified SV-CSF, the function of the influence are built by fitting the data to gamma distribution.

The viewing-condition-dependent SV-CSF model was proposed based on the measurement of CSF in different conditions. However, the experimental conditions were only one luminance, three viewing distances, etc., and the measured data is very coarse. Therefore, as the future work, we should measure more data. Moreover, for building the more accurate SV-CSF model, we should analysis and refine the measured data by referring the conventional data and models [19].

The motivation of this study is to evaluate and improve moving image quality of FPDs by using a SV-CSF model as human visual characteristics. Therefore, in the next stage, we should build evaluating and improving methods for moving pictures. In particular, MPRT measurement method should be revised by using the SV-CSF model. Furthermore, we would like to incorporate our model into the conventional methods for evaluating image quality such as S-CIELAB [20] and iCAM [21].

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