Measurement and Modeling of Chromatic Spatio-Velocity Contrast Sensitivity Function and its Application to Video Quality Evaluation

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Abstract

In this paper, we measured and modeled chromatic spatio-velocity contrast sensitivity functions (chromatic SV-CSFs). In addition, we applied our chromatic SV-CSF model to video quality evaluation. SV-CSF is a modulation transfer function of the human visual system, and consists of the relationship among contrast sensitivities, spatial frequencies and velocities of perceived stimuli. In our experiments, chromatic spatio-velocity contrast sensitivities (SV-CSs) were measured by using red-green and blue-yellow moving Gabor stimuli. From the results of chromatic SV-CSs measurements, it was shown that the chromatic SV-CSs had low-pass spatial frequency characteristics. In particular, the contrast sensitivities in the spatial frequencies over one cycle-per-degree decreased gradually as the velocities of the stimuli increased. From these results, we modeled the chromatic SV-CSFs based on Gaussian functions combined in spatial frequency and velocity domains. Furthermore, for evaluating color video quality, we applied our chromatic SV-CSF model to SV-CIELAB which is the video quality evaluation method using SV-CSF models. From the subjective experimental results for the validation, it was shown that SV-CIELAB using chromatic SV-CSF models is comparable to or better than conventional methods such as CIELAB color difference, Spatial-CIELAB and so on.

Introduction

Recently, due to the development and popularization of high-definition televisions, digital video cameras, Blu-ray discs, digital broadcasting, IP television and so on, high-quality videos have been widely used in our life. As high quality videos have become popular, it plays an important role to evaluate video quality.

Since image/video quality is perceived through the human visual system, a lot of image/video quality evaluation methods have been proposed by incorporating human visual characteristics. In particular, contrast sensitivity functions (CSFs) are frequently used as the human visual characteristics [1][2][3][4][5][6]. CSF is a criterion of visual sensitivity to contrast of different spatial and temporal grating patterns, and a lot of CSF models have been proposed [1][7][8][9][10][11][12]. Especially, it is said that spatio-velocity CSF (SV-CSF) is efficient to evaluate video quality [13]. SV-CSF consists of the relationship among contrast sensitivities, spatial frequencies and velocities of perceived stimuli. In the measurement and modeling of the conventional SV-CSFs[13][14][15], achromatic (luminance) grating stimuli were used. However SV-CSFs have been not measured and modeled by using chromatic grating stimuli.

In this research, therefore, we measured and modeled chromatic SV-CSFs. In our experiments, on the basis of the opponent color theory, chromatic spatio-velocity contrast sensitivities (SV-CSs) were measured by using red-green and blue-yellow moving grating stimuli. We also measured achromatic SV-CSs by using luminance stimuli to compare our measurement results with a conventional achromatic SV-CSF model. In the modeling, we constructed chromatic SV-CSF models for red-green and blue-yellow stimuli. We also investigated the accuracy of the proposed chromatic SV-CSF models by calculating the relative errors between the measurement data and the proposed models. Furthermore, we present an application of our chromatic SV-CSF models to color video quality evaluation.

Related Works

Spatio-Velocity Contrast Sensitivity Function

The frequency response characteristics in the human visual system are mostly described by CSFs which are the modulation transfer functions in the human visual system. In the measurements of contrast sensitivities, subjects observe grating stimuli designed based on sine patterns with various contrasts, and limits of distinguishable contrasts are obtained.

CSFs are mainly separated to four types: spatial, temporal, spatio-temporal and spatio-velocity types. A lot of CSF models have been proposed, and used to evaluate image/video quality in the practical applications. In particular, S. Daly suggested SV-CSF is useful to evaluate video quality [13]. In the measurements of SV-CSs [14][15], Gabor patterns were used as the grating stimuli which moved from left to right on a display device as shown in Fig.1. A fixation point is also displayed at the center of the stimuli and the point moved along the motion of the stimuli. The subjects are instructed to fix their gazes on the fixation point, and contrast sensitivities were measured.

Figure 2 represents the SV-CSF model [14]. The SV-CSF consists of the relationship among contrast sensitivities, spatial frequencies and velocities. The SV-CSF has band-pass characteristics and the peak of contrast sensitivities at 0 degrees-per-second (dps, the degrees means visual degrees) is around 3 cycles-per-degree (cpd). As the velocity increases, the peak becomes close to lower frequency.

Chromatic Contrast Sensitivity

In the research field of human color vision, chromatic contrast sensitivities have been also measured in spatial, temporal and spatio-temporal frequency domains [9][16][17]. In general, based

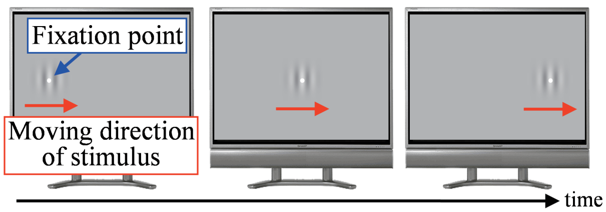


Figure 1. Moving Gabor stimulus in measurements of SV-CSF.

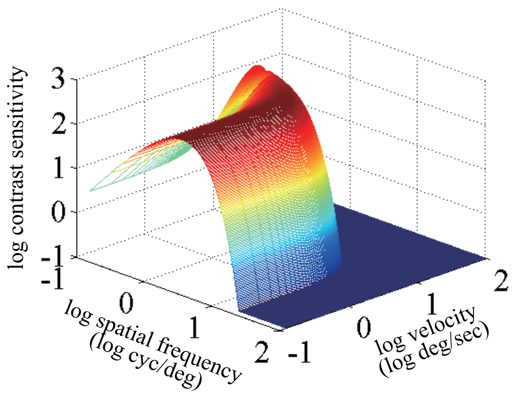


Figure 2. Achromatic SV-CSF model [14].

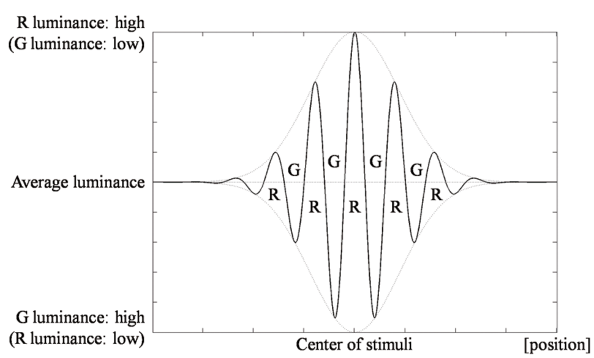


Figure 3. Stimulus in chromatic (red-green) contrast sensitivity measurement.

on the opponent color theory, red-green or blue-yellow stimuli have been used. In the measurements, as shown in Fig.3, the luminance of chromatic stimuli is stabilized [16]. The previous measurement results showed the chromatic CSFs have low-pass spatial frequency characteristics, with it regardless of the temporal characteristics.

Measurement and Modeling of Chromatic Spatio-Velocity Contrast Sensitivity

Measurement Method

In our measurement experiments, SV-CSs were measured using three kinds of stimuli: luminance, red-green and blue-yellow. The luminance stimuli were used for ascertaining whether the results in our measurements are the same as the ones in the conventional measurements. Table 1 shows the luminance and xy chromaticity of the presented stimuli. The xy chromaticity was decided based on the previous researched [16]. The stimuli were displayed on a 27" LCD display with 1980 $\times$ 1200 pixels.

Table 1. Luminance and xy chromaticity of stimuli.

Luminance stimuli	Luminance : 100 cd/m^2 Chromaticity : x=0.322, y=0.325
Red-green stimuli	Luminance : 38.5 cd/m^2 Red : x=0.644, y=0.329 Green : x=0.311, y=0.596 Background : x=0.525, y=0.424
Blue-yellow stimuli	Luminance : 12.2 cd/m^2 Blue : x=0.148, y=0.062 Yellow : x=0.525, y=0.424 Background : x=0.196, y=0.108

Table 2. Stimuli setups.

Stimuli pattern	Gabor pattern
Size	4 visual degrees
Spatial frequency	0.5, 1, 1.5, 2, 3, 4, 6, 8 cpd
Velocity	0, 10, 20 dps

Table 3. Experimental conditions.

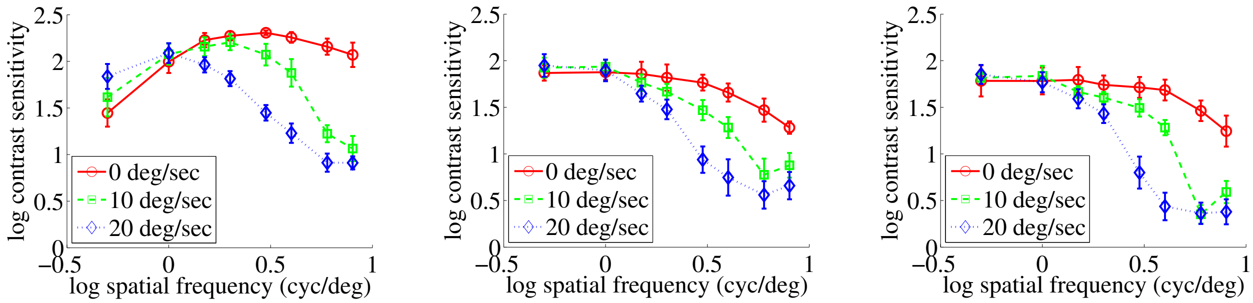
Display device	27" LCD (1980 $\times$ 1200 pixels)
Viewing distance	800 mm
Room condition	Dark room
Measurement method	Up-and-down method
Number of observers	13 observers in each condition

Table 2 and 3 show the stimuli and the experimental setups to measure SV-CSs. Gabor patterns of 4 visual degrees in diameter were used as the stimuli, and the stimuli patterns moved from left to right on the display as shown Fig.1. The subjects were instructed to fix their gaze on a fixation point on the stimuli. The spatial frequencies of the stimuli were 8 steps from 0.5 to 8 cpd which decided based on the previous studies about chromatic contrast sensitivities [16][17]. The velocities were 3 steps (0, 10 and 20 dps on the subject's retina) that were decided based on the previous report which surveys statistical characteristics of broadcast video signals [18]. In our experiment, an up-and-down method was used to obtain the thresholds of contrast sensitivities. Thirteen subjects observed the moving stimuli and judged whether the contrast was visible or not. The viewing distance is 800 mm.

Results and Discussion

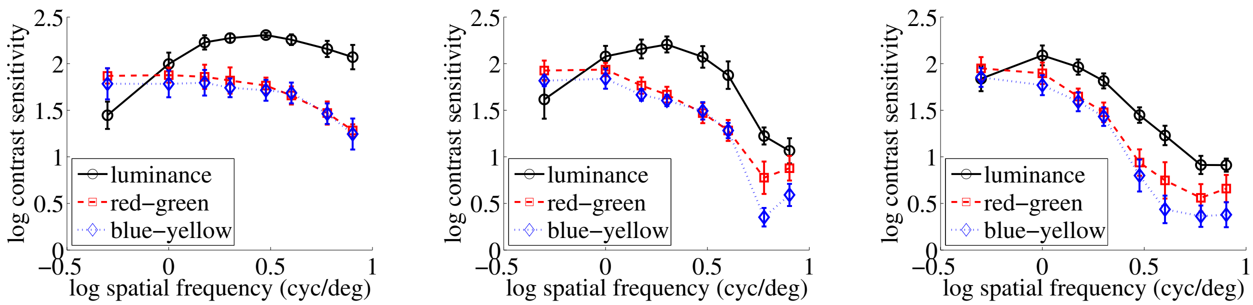
Figure 4 and 5 show the measurement results. In the experiments with luminance stimuli, our results are similar to the conventional ones [14]. To compare our measurement results with a conventional achromatic SV-CSF model [14], the relative error was calculated by the following equation.

$$e_{relative} = \sqrt{\frac{\sum_{\rho,v}(\mathrm{CS_m}(\rho,v) - \mathrm{CSF_a}(\rho,v))^2}{\sum_{\rho,v}\mathrm{CSF_a}(\rho,v)^2}} \qquad (1)$$



(a) Luminance stimuli (b) Red-green stimuli (c) Blue-yellow stimuli

Figure 4. *Results of chromatic contrast sensitivity measurement (Error bar: 95% confidence interval for the mean).*



(a) 0 dps (b) 10 dps (c) 20 dps

Figure 5. *Comparison of results among luminance, red-green and blue-yellow (Error bar: 95% confidence interval for the mean).*

where $\mathrm{CS_m}$ and $\mathrm{CSF_a}$ are the measured contrast sensitivities and the calculated ones by using the achromatic SV-CSF model, respectively. ρ and v are the spatial frequency in cpd and velocity in dps as shown in Table 2. The achromatic SV-CSF model is given by

$$
\begin{aligned}
\mathrm{CSF_a}(\rho,v) &= kc_0c_1c_2(v+c_v)(c_1 2\pi\rho)^2\exp\left(-\frac{c_1 4\pi\rho}{\rho_{\max}}\right)\\
k &= 6.1+7.3|log(c_2(v+c_v)/3)|^3\\
\rho_{\max} &= 45.9/(c_2(v+c_v)+2)
\end{aligned}
\tag{2}
$$

where c_0, c_1, c_2 and c_v are the parameters of the achromatic CSF model: c_0 = 1.85, c_1 = 0.56, c_2 = 0.48, and c_v = 5.1. In our study, the relative error was calculated by the following equation. In our study, the relative error between our results and the SV-CSF model are 23.5%. It is considered that the relative error is in an acceptable range considering the measurement errors shown in Fig.4. In other words, our measurement conditions were almost the same as the conventional ones. In the results of SV-CSs to both red-green and blue-yellow stimuli, the peaks of the contrast sensitivities become close to lower spatial frequency under one cpd, as the velocity of stimuli increases. In our experiments, the results of 0 dps stimuli have the similar tendency as the conventional studies [16][17]. The results of red-green stimuli are slightly higher than those of blue-yellow stimuli.

Modeling

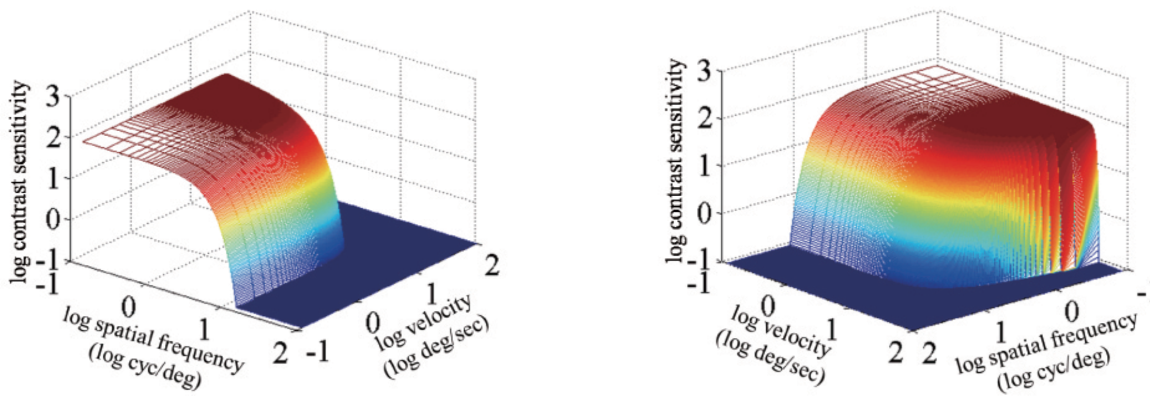
Based on the measurement results, we modeled a chromatic SV-CSF model. In the previous study [6], a chromatic CSF model was proposed based on a Gaussian function of spatial frequency. From this observation, the chromatic SV-CSF model was modeled by following equations.

$$
\begin{aligned}
\mathrm{CSF_c}(\rho,v) &= k\exp\left(-\frac{\rho^2}{2\sigma_1\sigma_v{}^2}\right)\\
\sigma_v &= \exp\left(-\frac{v^2}{2\sigma_2{}^2}\right)
\end{aligned}
\tag{3}
$$

where ρ is spatial frequency in cpd and v is the velocity in dps. k, σ_1 and σ_2 are parameters of the model that allow fine tuning. k controls the maximum contrast sensitivity, σ_1 does the contour of the model in the spatial frequency domain, and σ_2 does the contour in the velocity domain. σ_v is a Gaussian function of v and σ_2, which controls the contour in spatial frequency domain when changing the velocity of the stimuli. The parameter values found by optimization are as follows: k=78.1, σ_1=13.8 and σ_2 =14.2 for red-green stimuli, and k=65.8, σ_1=14.2 and σ_2 =13.1 for blue-yellow stimuli. Figure 6 represents our chromatic SV-CSF model for red-green stimuli. The contour of the SV-CSF model for blue-yellow stimuli is almost the same as the one for red-green stimuli. The relative errors given by Eq.(1) are 12.2 % for ref-green stimuli and 9.8 % for blue-yellow stimuli. Figure 7 and 8 show the comparison between the measurement results and our chromatic SV-CSF model.

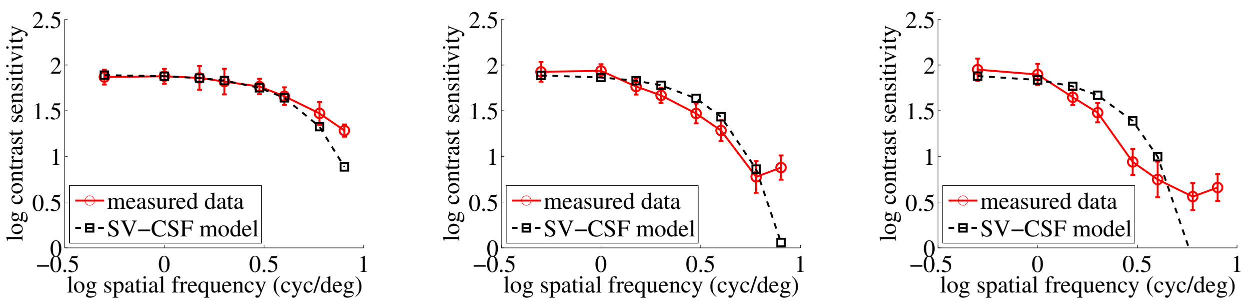
Application to Video Quality Evaluation

In this section, we present an application of the chromatic SV-CSF to SV-CIELAB which is a video quality evaluation method based on SV-CSF model [19]. SV-CIELAB was proposed to evaluate only gray-scale videos by using the achromatic SV-CSF model which is described above. In other words, SV-CIELAB could not take into account color video quality evalu-



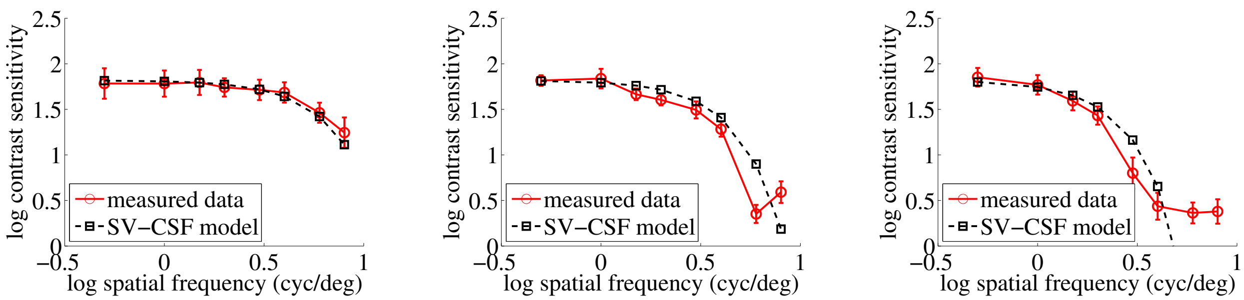
(a) Viewpoint #1 (b) Viewpoint #2

Figure 6. *Chromatic SV-CSF model for red-green stimuli.*



(a) 0 dps (b) 10 dps (c) 20 dps

Figure 7. *Comparison between result with red-green and our chromatic SV-CSF model (Error bar: 95% confidence interval for the mean).*



(a) 0 dps (b) 10 dps (c) 20 dps

Figure 8. *Comparison between result with blue-yellow and our chromatic SV-CSF model (Error bar: 95% confidence interval for the mean).*

ation enough, because chromatic SV-CSF models had not been proposed. Therefore, for evaluating color video quality, we incorporated our chromatic SV-CSF models into SV-CIELAB.

Overview of SV-CIELAB using achromatic and chromatic SV-CSF models

The calculation process in SV-CIELAB using the achromatic/chromatic SV-CSF models is almost the same as the conventional ones. Therefore, in this paper, we describe the overview briefly (See Ref.[19] for more details).

Figure 9 shows the overview of SV-CIELAB. As described in the previous sections, the SV-CSF models contain velocity axis. Therefore, first, the velocities at each pixel are acquired. To obtain the velocities, we calculated optical flows by using the Bergen's method [20]. In Bergen's method, gray-scale images are used for obtaining optical flows. So we used Y image in CIEXYZ color space for the optical flow calculation. Next, the original and distorted videos are separated to the opponent color channels: A(luminance), T(red-green), D(blue-yellow) of Guth's model in 1991 [21]. The videos separated at each channel are filtered using the optical flows and the SV-CSF model. As shown in Fig.10, we obtain video frames separated in spatial frequency domain for filtering. By using the velocity information, the frames separated at each spatial frequency are weighted by contrast sensitivities in the achromatic/chromatic SV-CSF models. A final filtered frame is obtained by synthesizing the weighted frames. Finally, the criteria in SV-CIELAB are obtained by calculating color differences between filtered original and distorted videos. To calculate the differences, the filtered videos are transformed to L*, a*, b* values in CIELAB color space. The color difference is computed

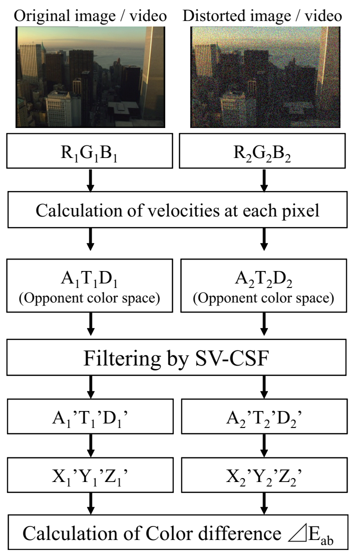


Figure 9. *Overview of SV-CIELAB.*

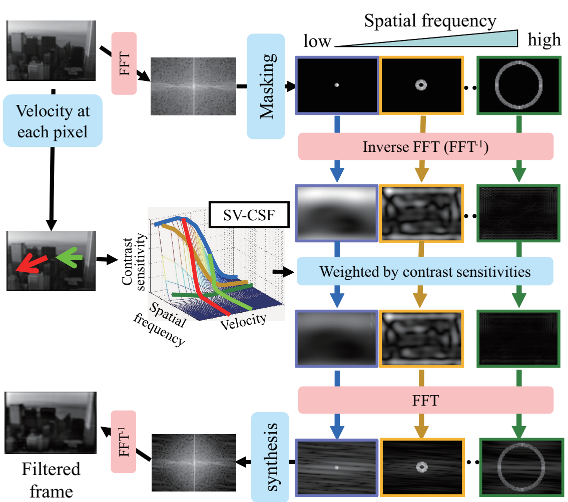


Figure 10. *Filtering in SV-CIELAB (Example of A(luminance) channel).*

pixel-by-pixel and then the mean difference between the videos is calculated as the criterion of SV-CIELAB.

Validation

For the validation of SV-CIELAB using the achromatic/chromatic SV-CSF models, subjective evaluation experiments were conducted. In the validation, subjective results were compared with SV-CIELAB and the conventional image/video quality evaluation methods which are PSNR (peak signal-to-noise ration), SSIM[22], CIELAB color difference, S-CIELAB[6] and ST-CIELAB[5].

In the experiments, we prepared four kinds of videos, which are the test samples of VQEG (video quality expert group). The distorted videos were generated by adding random noise of 0, 7.5, 10 and 12.5% and totally 16 videos were evaluated. The videos are 30 frames/second, the size is 256 $\times$ 256 pixels, and the time of each video is 20 seconds, which is generated by displaying a video of 10 seconds continuously. Fifteen observers participated in the subjective experiments. The original and distorted videos were presented at the same time on the left and right side of the display. The observers evaluated the degraded level by the scale of 1 to 5 (1: the same, 2: slightly different, 3: different, 4: definitely different and 5: very different). The display device is a 27" LCD (1920 $\times$ 1200 pixels) and the viewing distance is 400mm which are decided based on the standard viewing distance described in Ref.[18].

Figure 11 shows the results of the relationships between subjective and objective scores (SSIM, S-CIELAB and SV-CIELAB which is extended to evaluate color video quality). Table 4 also shows Spearman's rank order correlation coefficients [23] between subjective and objective scores. As shown in Fig.11 and Table 4, the extended SV-CIELAB to evaluate color video quality is comparable to or better than the conventional image/video quality evaluation methods.

Conclusions

In this research, we measured and modeled chromatic SV-CSFs. The measurement results show low-pass characteristics, and the peaks of contrast sensitivities appear in lower spatial frequency as the velocity increases. From the results, we constructed the chromatic SV-CSF model based on Gaussian functions. In our study, we also applied our chromatic SV-CSF model to SV-CIELAB for evaluating color video quality. From the experimental results for the validation, it was shown that the SV-CIELAB is comparable to or better than the conventional methods which are PSNR, SSIM, CIELAB color difference, S-CIELAB and ST-CIELAB.

As future work, it would be interesting to incorporate visual attention models using motion information to SV-CIELAB, because information of visual attention is effective in image/video quality evaluation. In particular, motion information is significantly related with SV-CSs and visual attention while viewing videos. Therefore, we will employ visual attention areas based on motion information for a high-performance video quality evaluation method.

Acknowledgments

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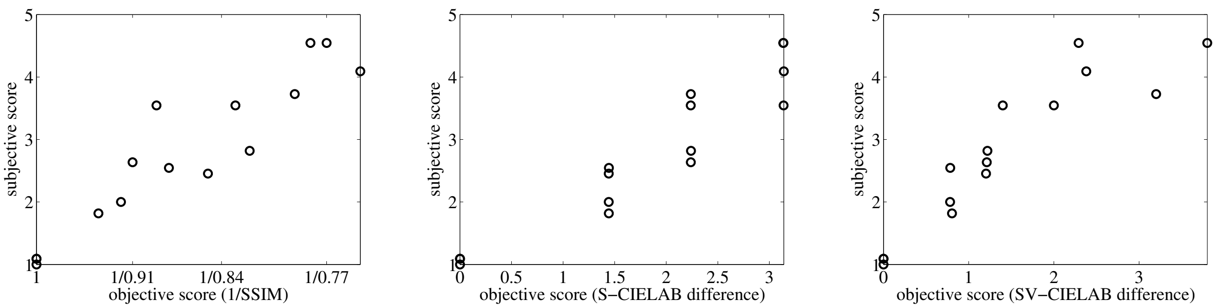
References

[1] P. G. J. Barten: "Contrast Sensitivity of the Human Eye and Its Effects on Image Quality", SPIE press, Bellingham, WA (1999).
[2] S. Daly: "Digital Image and Human Vision", MIT Press, Cambridge, MA, pp.179-206 (1993).
[3] T. O. Aydin, R. Mantiuk, K. Myszkowski, and H. P. Seidel: "Dynamic Range Independent Image Quality Assessment", ACM Trans. on Graphics (Proc. SIGGRAPH), **27**, 3, pp.69:1-10 (2008).
[4] K. Hirai, T. Nakaguchi, N. Tsumura, and Y. Miyake: "Correlation analysis between motion blur width and human perception", Proc. 14th International Display Workshops, pp.1201-1204 (2007).



(a) SSIM. (b) S-CIELAB. (c) SV-CIELAB.

Figure 11. *Relationships between subjective and objective scores. The SV-CIELAB is the extended version using the chromatic SV-CSF models for evaluating color video quality. Note that the values of horizontal axes in (a) are reciprocals of SSIM.*

Table 4. Rank order correlation coefficients (ROCC) between subjective and objective scores.

	PNSR	SSIM	CIELAB	S-CIELAB	ST-CIELAB	SV-CIELAB
ROCC	0.831	0.886	0.847	0.855	0.869	0.912

[5] X. Tong, D. Heeger, and C.B. Lambrecht: “Video quality evaluation using ST-CIELAB”, Proc. SPIE, **3644**, pp.185-196 (1999).

[6] X. Zhang, and B. A. Wandell: “A spatial extension of CIELAB for digital color image reproduction”, SID Symposium Digest, **27**, 1, pp.731-734 (1996).

[7] D. H. Kelly: “Motion and vision. I. Stabilized images of stationary gratings”, J. of Opt. Soc. Am., **69**, 9, pp. 1266-1274 (1979).

[8] D. H. Kelly: “Motion and vision. II. Stabilized spatio-temporal threshold surface”, J. of Opt. Soc. Am., **69**, 10, pp.1340-1349 (1979).

[9] D. H. Kelly: “Visual Science and Engineering: Models and Applications”, Marcel Dekker Inc., New York, pp.91-114 (1994).

[10] C. W. Thomas, G. C. Gilmore, and F. L. Royer: “Models of contrast sensitivity in human vision”, IEEE Trans. on systems, man, and cybernetics, **23**, 3, pp.857-864 (1993).

[11] Y. Miyake, T. Ishihara, K. Ohishi, and N. Tsumura: “Measurement and Modeling for the Two Dimentional MTF of Human Eye and its Application for Digital Color Reproduction”, Proc. of IS&T/SID’s 9th Color Imaging Conference, pp.153-157 (2001).

[12] P. G. J. Barten: “Formula for the contrast sensitivity of the human eye”, Proc. SPIE, **5294**, pp.231-238 (2004).

[13] S. Daly: “Engineering observations from spatiovelocity and spatiotemporal visual models”, Proc. SPIE, **3299**, pp.180-191 (1998).

[14] K. Hirai, N. Tsumura, T. Nakaguchi, and Y. Miyake: “Measurement and Modeling of Viewing-Condition- Dependent Spatio-Velocity Contrast Sensitivity Function”, Proc. of IS&T/SID 15th Color Imaging Conference, pp.106-111 (2007).

[15] J. Laird, M. Rosen, J. Pelz, E. Montag, and S. Daly: “Spatio-Velocity CSF as a Function of Retinal Velocity using Unstabilized Stimuli”, Proc. SPIE, **6057**, pp.605705:1-12 (2006)

[16] D. H. Kelly: “Spatiotemporal cariation of chromatic and achromatic contrast thresholds”, J. of Opt. Soc. of Am., **73**, 6, pp.742-750 (1983).

[17] K. T. Mullen: “The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings”, J. Physiol., **359**, pp.381-400 (1985).

[18] Y. Yoshida, T. Fujine, Y. Kikuchi, and M. Sugino: “Real-Life In-Home Viewing Conditions for FPDs and Statistical Characteristics of Broadcast Video Signal”, Proc. of 1st Japan Workshop on Image Media Quality and Its Applications, pp.7-10 (2006).

[19] K. Hirai, J. Tumurtogoo, A. Kikuchi, T. Nakaguchi, N. Tsumura, and Y. Miyake: “SV-CIELAB: Video Quality Assessment using Spatio-Velocity Contrast Sensitivity Function”, Proc. of IS&T/SID 17th Color Imaging Conference, pp.35-41 (2009).

[20] J. R. Bergen, P. Anandan, K. J. Hanna, and R. Hingorani: “Hierarchical model-based motion estimation”, Proc. of the European Conference on Computer Vision, pp.237-252 (1992).

[21] S. L. Guth: “Model for color vision and light adaptation”, J. of Opt. Soc. Am. A, **8**, 6, pp.976-993 (1991).

[22] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli: “Image quality assessment: From error visibility to structural similarity”, IEEE Trans. on Image Processing, **13**, 4, pp.600-612 (2004).

[23] C. Spearman: “The proof and measurement of association between two things”, Amer. J. Psychol., **15**, pp.72-101 (1904).

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