Critical Fusion Frequency for Bright and Wide Field-of-View Image Display

Masaki Emoto and Masayuki Sugawara

***Abstract*—The use of bright and wide field-of-view (FOV) displays in future TV systems will enable us to enjoy TV programs with a rich sense of presence, i.e., a sense of "being there." However, such displays can strongly stimulate human peripheral vision, which is sensitive to flicker. The recent widespread adoption of hold-type displays such as liquid crystal displays might circumvent the flicker problem in current TV systems. For temporal specification of future TV systems with bright and wide FOV displays, we measured the critical fusion frequency (CFF) in 26 participants, using varying luminance, duty ratios, and FOVs. We showed that CFF depended on the duty ratio and the FOV, and that more than 90 Hz was required to avoid flicker perception with wide FOV displays. Moreover, we demonstrated that flicker was regularly perceived in viewing wide FOV natural images presented at 60 Hz with a 50% duty ratio.**

***Index Terms*—Critical fusion frequency (CFF), duty ratio, flicker, frame rate, luminance, wide field of view (FOV).**

I. Introduction

ULTRA-HIGH-DEFINITION TV (UHDTV) with a wide field of view (FOV) has been proposed as a future broadcasting system [1], [2]. The UHDTV system has a high spatial resolution (4320 scan lines by 7680 horizontal pixels), and this spatial resolution enables viewers to feel as though they are in the space displayed by the video system [3], [4]: this is often referred as a sense of presence or of "being there." The horizontal FOV provided by the UHDTV system exceeds 100 deg, whereas the FOV provided by HDTV is approximately 30 deg. Although there have been substantial advances in the spatial resolution of UHDTV, a temporal resolution adequate for the wide FOV display system has not yet been established. It is mandatory to decide on an adequate temporal resolution for wide FOV TV systems, and to achieve this we are studying the temporal resolution of human vision.

If the temporal resolution of a wide FOV TV system is not high enough, viewers could perceive flicker of the displayed images. Flicker is very annoying and can cause not only degradation of picture quality but also visual fatigue and even photosensitive seizures [5], [6]. It is therefore very important for system designers to eliminate flicker. Accordingly, future broadcasting systems with wide FOV displays will also need to be designed to be flicker free and will need to be optimized for wide FOV.

Traditional TV systems—namely, NTSC (National Television System Committee), PAL (Phase Alternating Line), and SECAM (SEquentiel Couleur A Mémoire)—have frame frequencies sufficiently high for viewers not to perceive flicker under certain viewing conditions, including when the FOV image display is fairly dark and narrow. Use of a high frame frequency can eliminate flicker perception, but economical use of bandwidth for recording and transmission must be considered simultaneously. The relationship between frame frequency and bandwidth is therefore a trade-off. It is desirable to decide on the lowest frame frequency at which flicker perception can be eliminated. To make this decision, the characteristics of human flicker perception—and the flicker threshold—need to be elucidated under the conditions that will be used in the future for viewing wide FOV TV.

The threshold of flicker perception is called the critical fusion frequency (CFF) or flicker fusion threshold, and it typically ranges from 30 to 60 Hz at the fovea. The CFF depends on many factors, including stimulus size, locus of retinal stimulation, illumination of the TV surround, adaptation level of the viewer, and temporal pattern of stimulation or stimulus waveform [7], [8]. A number of studies of CFF have been conducted [9]. An adequate frame frequency for future TV systems with a wide FOV should be determined by taking into account both past basic studies and new studies conducted under new viewing conditions for wide FOV TV.

The specifications for traditional TV systems were determined from studies conducted using cathode ray tubes (CRT). The specifications included frame frequency, luminance of the image display, duty ratio of the display, decay of the light in the image display, and the image FOV.

In a pioneer 1935 study before the Electronic Industry Alliance RS-170 standard was set, Engstrom conducted CFF measurement experiments assuming a screen illumination of 20 footcandle (fc) and a 3:4 aspect ratio CRT, with 12.68 degrees FOV and a duty ratio ranging from 2.7% to 97.2% [10]. Flicker was perceivable at 24 frames per second (fps) but not at 48 fps. In consideration of the instability of power sources at that time, 60 fps was recommended by the Electronics Industries Alliance. For standardization of future TV system specifications, we should assume bright and wide FOV displays. The use of high-luminance displays and peripheral vision stimulation will strongly affect the CFF; new temporal specifications are therefore needed for future TV systems. UHDTV has an FOV display that is more than 100 degrees wide when viewed at 0.75 times the display height, whereas the FOV display is approximately 10 degrees [10] wide on traditional TV and approximately 30 degrees on HDTV. When viewers watch HDTV with 30 degrees FOV, the most sensitive retinal position corresponding to 40 degrees of eccentricity is outside the image area, even if the viewer fixates on the left or right edge of the image area. On the other hand, when viewers

Manuscript received December 21, 2011; revised February 23, 2012, March 07, 2012; accepted March 13, 2012. Date of publication April 30, 2012; date of current version June 28, 2012.

The authors a are with the Science & Technology Research Laboratories, Japan Broadcasting Corporation (NHK) Setagaya-ku, Tokyo 157-8510, Japan (e-mail: emoto.m-hy@nhk.or.jp).

Digital Object Identifier 10.1109/JDT.2012.2191390

TABLE I
COMBINATIONS OF ND FILTERS AND MEASURED LUMINANCES AT EACH DUTY RATIO

Duty ratio	ND filter 1	ND filter 2	Luminance (cd/m^2)	ND filter 1	ND filter 2	Luminance (cd/m^2)	ND filter 1	ND filter 2	Luminance (cd/m^2)
	Intended luminance 169 cd/m^2			Intended luminance 315 cd/m^2			Intended luminance 480 cd/m^2		
10%	0%	0%	169						
20%	0%	50%	167	0%	0%	315			
30%	70%	50%	170	0%	70%	329	0%	0%	480
40%	25%	0%	168	0%	50%	314			
50%	0%	20%	168	0%	40%	314	90%	70%	507
60%	40%	40%	161	70%	50%	330	0%	50%	477
70%	70%	20%	166	90%	30%	306	90%	50%	507
80%	25%	50%	168	0%	25%	318	90%	40%	463
90%	90%	13%	176	90%	25%	328	70%	50%	503

watch wide FOV displays such as UHDTV, the most sensitive retinal position may be included in the image area. Therefore, flicker perception and its ill effects on image quality might be a problem specific to the wide FOV system, whereas flicker perception might be negligible in narrow FOV systems.

Brighter TV displays than before are now in commercial use; their maximum luminance is reaching 450 cd/m^2, whereas the preferred luminance in a living room is about 240 cd/m^2 [11]. Flicker tends to be perceived with bright displays, so CFF needs to be studied with such displays. If flicker perception is confirmed in the bright and wide FOV display system, then this system will need greater temporal resolution or a higher frame frequency than traditional TV systems.

Notably, liquid crystal displays (LCD) cannot flicker. In recent years, flat panel LCDs and LCD projectors have been popular as TV monitors. Use of this technology might circumvent the flicker problem, because LCDs hold pixel luminance until the next refresh time point. (The length of time between refreshes is typically the reciprocal of the frame frequency). With hold-type displays such as LCDs there can be image blur of fast-moving objects [12]. Measures to decrease the degradation of the motion image quality on hold-type displays have been proposed; they include insertion of black between frames [13] and the use of a high frame frequency to shorten the hold period [14]. In other words, this trend might represent a migration from the flat panel LCD to traditional impulse-type displays such as the CRT. The flicker problem would be conspicuous if displays were to return to the impulse type or if they were to progress to some kind of new design approaching the impulse type.

Flicker perception is one of the factors that should be considered in deciding on an appropriate temporal resolution for future wide FOV TV systems. To characterize the parameters of the visual systems of humans viewing a wide FOV display, we studied changes in viewers' flicker perceptions by measuring CFFs with varying duty ratios. Two experiments were conducted. In experiment 1, with 100 degrees FOV, the duty ratio, which is the main independent variable, varied from 10% (near impulse-type display) to 90% (almost hold-type display). Fig. 1 defines the term 'duty ratio'. Target luminances were 169, 315, and 480 cd/m^2. In experiment 2, with 30 and 100 degrees FOV (the main independent variable), CFFs were measured at the most sensitive duty ratio for each viewer. Target luminances were again 169, 315, and 480 cd/m^2. CFF was determined by allowing participants to adjust the frequency of the flickering visual stimuli themselves.

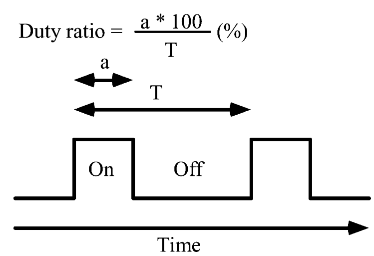

Fig. 1. Duty ratio is defined as the ON duration (a) as a proportion of the ON+OFF duration (T).

II. METHODS

A. Viewing Conditions

FOV was set to 100 degrees in experiment 1. An additional CFF measuring trial at 30 degrees FOV was conducted at the most sensitive duty ratio in experiment 2 to determine the difference in flicker perception between UHDTV and HDTV conditions. The aspect ratio was 9:16 in both systems. White luminance on the screen without a neutral density (ND) filter, as measured with a luminance colorimeter with a 2-s time aperture and 2 degrees FOV, was 169, 315, or 480 cd/m^2. Black luminance was 4 cd/m^2. Background luminance was 0.5 cd/m^2. A viewing distance of approximately 10 cm was used to achieve the desired luminances and FOV despite the small image presentation size. The luminances of the flicker sequences, which varied according to the changes in the duty ratio, were kept almost constant by using adequate ND filters. Table I shows the three intended target luminances, the measured target luminances, and the combinations of ND filters used (0% = no ND filter). The blanks in the table show that combining two ND filters to obtain the approximate intended luminances was impossible. There were some differences between intended and measured target luminances. In the first

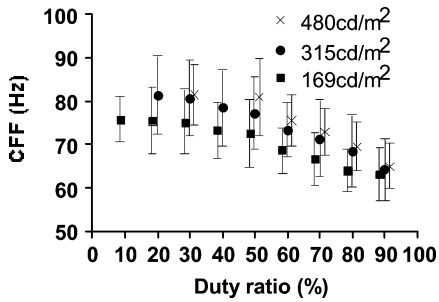

Fig. 2. Mean critical fusion frequency (CFF) and standard deviation plotted against duty ratio. CFF decreased with increasing duty ratio and was higher at higher luminances.

trial, the order of duty ratios was chosen in such a way as to change the ND filters around in the most efficient way. The order in the second trial was the reverse of that in the first trial; the order in the third trial matched that of the first trial. Consequently, three trials per duty ratio for each target luminance were conducted.

B. Apparatus

The apparatus consisted of a projector, a rear-projection screen, a 10-key keyboard for noting the viewers' responses, and a chin-rest. The video projector consisted of an XGA (extended graphics array) digital micro-mirror device (DMD, Texas Instruments Inc.) with a 150-W xenon arc lamp, relay optics with a zoom lens (Sigma APO 50–150 mm), and ND filters. We presented flicker sequences consisting of black or white at various temporal frequencies up to approximately 200 Hz and at various duty ratios. Viewers put their heads on a chin-rest and were instructed to control the temporal frequency of the visual target at their CFF by pressing the "+" or "−" keys. The rear-projection screen was masked for the flicker sequences to give approximately 100 or 30 degrees of horizontal FOV and a 9:16 aspect ratio. We used a high-speed camera and image recorder with a video monitor (Plextor PL-1/M20) to confirm that the flicker sequences were adequately presented. The luminance of the visual target was measured with a luminance colorimeter (Topcon BM-7).

C. Participants

Twenty-six healthy adults (3 male and 23 female; mean age: 31.7 years, range: 24–34), participated in the experiments after providing signed informed consent. All participants had normal visual functions and static visual acuity ranging from 0.4 to 2.0 (decimal values). Eight participants corrected their vision with contact lenses and five with eyeglasses; 13 required no correction.

D. Data Analysis

CFF was determined as the average CFF of the three trials for each duty ratio and target luminance. Repeated measures analysis of variance (ANOVA) [15] and contrasts were performed in the case of experiment 1. CFFs between duty ratios of 30% and 50%, 50% and 60%, 60% and 70%, 70% and 80%, and 80% and 90% were compared. A paired t-test was performed to compare CFFs for narrow and wide FOVs in experiment 2.

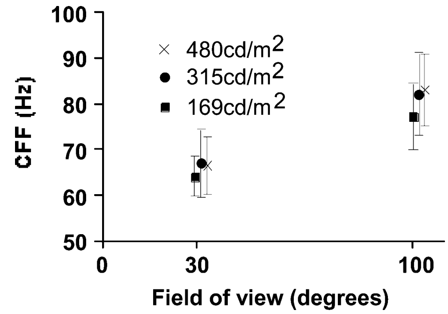

Fig. 3. Mean critical fusion frequency (CFF) and standard deviation plotted against field of view (FOV). With a wide FOV, the CFFs were beyond 80 Hz at high target luminances and were higher than those with a narrow FOV.

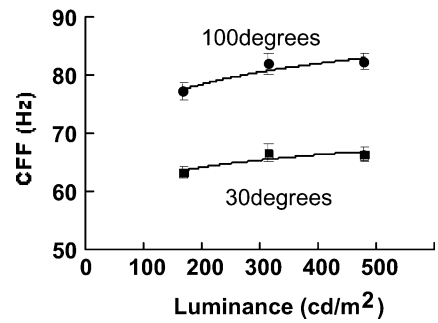

Fig. 4. Screen luminance and critical fusion frequency (CFF) with 30 and 100 degrees FOV. Two regression curves show the CFF prediction equations by Farrell *et al.* [16] CFF was above 60 Hz at 30 degrees FOV and above 80 Hz at high target luminance at 100 degrees FOV.

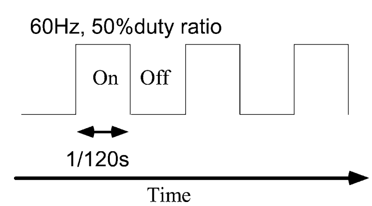

Fig. 5. Intensity of light presented at 60 Hz with a 50% duty ratio. ON and OFF duration were both 1/120 s.

III. Results

A. Experiment 1: Dependency of CFF on Duty Ratio

We plotted the mean CFFs $(N = 26)$ and standard deviations at FOV 100 degrees when the duty ratio was varied from 10% to 90% at three target luminances (Fig. 2). Missing points in the figure at 10% duty ratio (315 cd/m^2) and at 20, 40% duty ratio (480 cd/m^2) correspond to the blanks of the Table I. CFF decreased from a maximum of 80–65 Hz with increasing duty ratio. Repeated measures ANOVA with two within-participant factors (3 target luminances and 6 duty ratios) was performed. The duty ratios were 30%, 50%, 60%, 70%, 80%, and 90% and were common to the 3 target luminances. When Mauchly's assumption of sphericity was not assumed, we corrected the degree of freedom by using Greenhouse-Geisser $\mathrm{epsilon} = 0.413$ for the duty ratios, and $\mathrm{epsilon} = 0.405$ for the interaction of target luminance x duty ratio. There were significant differences in CFFs among target luminances $(F(2,50) = 21.0, P < 0.001)$ and in CFFs among duty ratios $(F(2.07, 51.7) = 139.2, P < 0.001)$, without interaction $(F(4.05, 101.3) = 1.759, P = 0.142)$. The contrast showed

Couple

Eiffel

Fig. 6. Images presented (named (a) Couple [upper] and (b) Eiffel [bottom] in accordance with the Institute of Image Information and Television Engineers' HDTV chart [18]). Participants were instructed to view the images while standing and to report whether they perceived flicker. Viewing distances were 0.75, 1.5, 3.0, and 6.0 times the image height, with horizontal fields of view of approximately 99.7, 61.3, 33.0, and 16.8 degrees, respectively.

significant differences in CFFs between all pairs of adjacent duty ratios at $P < 0.001$. The F(1, 25) values were 22.6, 62.2, 22.9, 66.3, and 56.3 for 30% with 50%, 50% with 60%, 60% with 70%, 70% with 80%, and 80% with 90%, respectively.

B. Experiment 2—Dependency of CFF on FOV

We investigated the mean CFFs $(\mathrm{N} = 26)$ and standard deviations at FOVs of 30 and 100 degrees at three target luminances $(169, 315, 480\ \mathrm{cd/m^2})$ (Fig. 3). The CFFs of the wide FOV were beyond 80 Hz at high target luminances and were higher than the CFFs of the narrow FOV (about 65 Hz). A paired t-test showed significant differences between the CFFs for narrow and wide FOVs in experiment 2 $(t(77) = 0.00, P < 0.001)$.

These results demonstrated that CFF decreased with increasing duty ratio. This suggests that viewers perceive flicker more sensitively in impulse-type displays than in hold-type displays, and that flicker perception (or the decrease in image quality introduced by the flicker) might be a problem specific to wide-FOV display systems.

IV. Discussion

Farrell *et al.* proposed a CFF prediction equation using mean screen luminance over time, the amount of light reflected from the screen when the display is off, the diameter of the viewer's pupil, the DC component of the temporally varying screen luminance, and the amplitude coefficient [16]. To verify the applicability of their equation to our data, we fitted our data to their equation and obtained a slope parameter m, intercept n, and coefficient of determination R^2 $(m = 37.41, n = 3.510, R^2 = 0.7746$ for 30 degrees; $m = 34.11, n = 5.821, R^2 = 0.8876$ for 100 degrees). We examined the relationship between screen luminance along the abscissa and CFF along the ordinate by plotting the measured regression curves for each FOV (Fig. 4). CFF did not exceed 90 Hz at extremely high screen luminance, and it seemed to become saturated at high screen luminances (beyond 300 cd/m^2). We surmised that this saturation was due partly to physiological pupil control, because Tyler has reported that, when observers' pupils are dilated with 0.5% mydriacyl, the most sensitive location on the retina occurs at 40 degrees

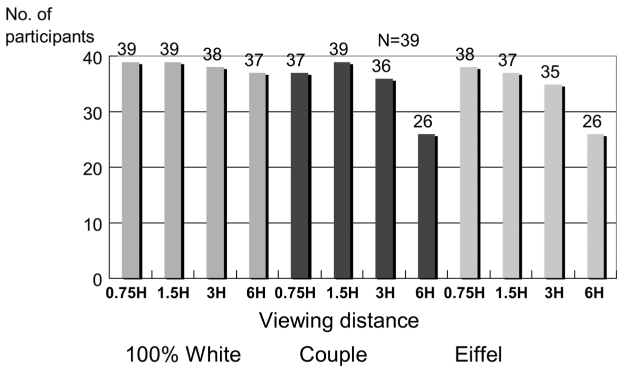

Fig. 7. Numbers of participants reporting flicker at each viewing distance ($H = \mathrm{image}$ height). Almost all participants reported flicker perception at close viewing distances, and two-thirds reported flicker at the farthest viewing distance (6H). Images were as in Fig. 6.

of eccentricity and the CFF is beyond 100 Hz [17]. This suggests that bright and wide FOV displays with low duty ratios need frame frequencies of more than 90 Hz. However, an increase in frame frequency directly causes the system bandwidth for recording, transmitting, and display to increase.

We conducted an additional experiment to verify the perception of flicker of natural TV images presented at 60 Hz with a 50% duty ratio. We first developed an apparatus that could present HDTV images at 240 Hz. Two successive frames of an identical natural image and two successive frames of black were loaded into a hard disk playback signal source (Keisoku Giken Co., Ltd. UDR20S). They were played back at 240 Hz to present images at 60 Hz with a 50% duty ratio. We examined the intensity of light under these conditions (Fig. 5). A newly developed LCoS (Liquid Crystal on Silicon) projector based on the Sony SRX-S110 projector was used to project the images at a peak luminance of 270 cd/m^2 on a 100-inch rear-projection screen. Thirty-nine participants were instructed to view the screen while standing and to report whether they perceived flicker or not. Their viewing distances were 0.75, 1.5, 3.0, and 6.0 times the image height (i.e., 6H), with horizontal FOVs of approximately 99.7, 61.3, 33.0, and 16.8 degrees, respectively. The images presented were named 100% White, Couple, and Eiffel in accordance with the Institute of Image Information and Television Engineers' HDTV test chart [18]. Fig. 6 shows (a) Couple and (b) Eiffel. Fig. 7 shows the numbers of participants who reported flicker at each viewing distance. Almost all participants reported flicker at near viewing distances, and two-thirds of participants reported flicker at the farthest viewing distance (6H) when viewing Couple and Eiffel. This result showed that perception of flicker in natural images depended on the viewing distance and, therefore the FOV; our finding that at 6H the number of viewers perceiving flicker in the 100% White image was greater than the number perceiving it in the other two images (Fig. 7) suggested that flicker perception also depended on the image content. The brighter the luminance, the more sensitive to flicker we become (see Fig. 4). However, Fig. 4 shows that CFF tends to reach a plateau with increasing luminance. This suggests that the CFF will not exceed 100 Hz under ordinary home TV viewing conditions, but that 60 Hz is insufficient to prevent flicker perception with non-hold-type displays. Recent commercial use of 120- or 240-Hz-driven LCD TV suggests the technical validity of increasing the temporal resolution of future TV broadcasting systems.

V. Conclusion

Wide FOV flicker perception and its ill effect on image quality might be a problem specific to wide FOV systems, and flicker perception might be negligible in HDTV. We studied changes in viewers' flicker perception by measuring CFF under varying duty ratios to elucidate the characteristics of the human visual system in viewing wide FOV TV. The results demonstrated that CFF decreased with increasing duty ratio. This suggests that viewers are more likely to perceive flicker in impulse-type displays than in hold-type displays, and that flicker perception or the decrease in image quality introduced by flicker is a problem specific to wide-FOV display systems. An additional experiment on flicker perception in natural images presented at 60 Hz with a 50% duty ratio showed that almost all participants perceived flicker with wide FOV presentation. It is very important to optimize the trade-off relationship between flicker and motion-blur perception to give optimum image quality at a frame frequency of about 60 Hz. However, the best way to solve the problem of motion blur and image quality degradation introduced by the flicker is to increase the system's frame frequency. It is essential to determine an adequate system frame frequency for wide FOV systems.

References

[1] M. Kanazawa *et al.*, "An ultrahigh-definition display using the pixel-offset method," *J. SID*, vol. 12, pp. 93–103, 2004.
[2] M. Sugawara *et al.*, "Ultrahigh-definition video system with 4000 scanning lines," *SMPTE Motion Imag.*, vol. 112, pp. 339–346, 2003.
[3] T. Hatada, H. Sakata, and H. Kusaka, "Psychophysical analysis of the 'sensation of reality' induced by a visual wide-field display," *SMPTE J.*, vol. 89, pp. 560–569, 1980.
[4] M. Emoto, K. Masaoka, M. Sugawara, and Y. Nojiri, "The viewing angle dependency in the presence of wide field image viewing and its relationship to the evaluation indices," *Displays*, vol. 27, pp. 80–89, 2006.
[5] G. F. A. Harding and P. M. Jeavons, *Photosensitive Epilepsy (New Edition)*. London, U.K.: MacKeith, 1994.
[6] G. F. A. Harding, "TV can be bad for your health," *Nat. Med.*, vol. 4, pp. 265–267, 1998.
[7] J. L. Brown, , C. H. Graham, Ed., "Vision and Visual Perception," in *Flicker and Intermittent Stimulation*. New York: Wiley, 1966, pp. 251–320.
[8] A. B. Watson, , K. Boff, L. Kaufman, and J. Thomas, Eds., "Handbook of Perception and Human Performance 1," in *Temporal Sensitivity*. New York: Wiley, 1986.
[9] C. Landis, *An Annotated Bibliography of Flicker Fusion Phenomena*. Ann Arbor: Univ. of Michigan Press, 1953, pp. 1740–1952.
[10] E. W. Engstrom, "A study of television image characteristics, part two," in *Proc. Inst. Radio Eng.*, 1935, vol. 23, pp. 295–310.
[11] T. Fijine, Y. Yoshida, and M. Sugio, "The relationship between preferred luminance and TV screen size," in *Proc. SPIE, Image Qual. Syst. Perform.*, 2008, vol. 6808, pp. 68080Z.1–68080Z.12.
[12] G. de Haan and M. A. Klompenhouwer, "Temporal aspects of emerging displays," in *Digest of the ICCE'01*, Los Angeles, CA, 2001, pp. 42–43, ICCE.
[13] K. Sueoka, H. Nakamura, and T. Taira, "Improving moving-image quality of TFT-LCDs," in *Dig. Tch. Papers 1997 SID Int. Symp.*, 1997, pp. 203–207.
[14] Y. Kuroki, T. Nishi, S. Kobayashi, H. Oyaizu, and S. Yoshimura, "A psychophysical study of improvements in motion-image quality by using high frame rates," *J. SID*, vol. 15, pp. 61–68, 2007.
[15] J. R. Jennings, "Editorial policy on analyses of variance with repeated measures," *Psychophysiol.*, vol. 24, pp. 474–475, 1987.
[16] J. E. Farrell, B. L. Benson, and C. R. Haynie, "Predicting flicker thresholds for video display terminals," in *Proc. SID*, 1987, vol. 28, pp. 449–453.
[17] C. W. Tyler, "Analysis of visual modulation sensitivity. III. Meridional variations in peripheral flicker sensitivity," *J. Opt. Soc. Amer. A*, vol. 4, pp. 1612–1619, 1987.
[18] *Test Materials to be Used in Subjective Assessment*, Rec. ITU-R BT.1210-1, ITU, 1997.

Masaki Emoto (M'03) received the B.S. and M.S. degrees in electronic engineering and the Ph.D. degree in human and environmental studies from Kyoto University, Kyoto, Japan, in 1986, 1988, and 2003, respectively.

He has been working on future television systems and human science, especially human visual sysetm, at NHK Science and Technical Research Laboratories. His research interests include future television systems incorporating desirable effects such as a heightened sensation of presence, and eliminating undesirable side effects to the viewer such as photosensitive response, visually induced motion sickness, and visual fatigue.

Masayuki Sugawara received the B.S. and M.S. degrees in electric communication engineering, and the Ph.D. degree in electronic engineering from Tohoku University, Sendai, Japan.

He joined NHK (Japan Broadcasting Corporation), Tokyo, Japan, in 1983. Since 1987, he has been researching the solid-state image sensor and HDTV camera at the Science and Technical Research Laboratories (STRL). He was an associate professor at the University of Electro-Communications in Tokyo from 2000 until 2004. Currently, he is an Executive Research Engineer at NHK STRL and engaged in the research of ultrahigh-definition TV systems.

Dr. Sugawara is a member of SMPTE, IEICE, and ITE.