Effects of motion image stimuli with normal and high frame rates on EEG power spectra: comparison with continuous motion image stimuli

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***Abstract* —** The human electroencephalographic (EEG) power spectra when viewing visual stimuli of a real motion image and of motion images with 60 frames/s (fps) and 240 fps were investigated. The EEG spectra in response to the 240 fps motion image stimuli were more similar to those of the real motion image stimuli than those of the 60 fps stimuli. This high frame rate (240 fps) motion image is considered to have a possibility of providing perceptions of motion image quality that are close to the impression upon looking at real world scenes.

Keywords — *60 and 240 fps, visual stimulation, real (continuous) motion image, motion image quality, blur, jerkiness, EEG spectral analysis.*

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1 Introduction

In recent development of image technologies, there is a trend of increasing resolution from high definition (HD; 1920 × 1080 pixels) by two or four times in height and width.[1] As a motivation driving this trend, there is a desire of viewers for higher immersive effects of motion images. It has been reported that wide viewing angle is effective for increasing the immersive effect.[2] High spatial resolution enables high image quality even in cases of viewing with large viewing angles. In addition, recent research in motion images has shown that higher frame rate improves image quality by reducing elements of motion impairment such as blur and jerkiness.[3–6] Therefore, it is considered that high frame rate is one of the effective specifications for enhancing highly immersive motion images.

However, studies of the relationship between motion image quality and frame rate have been carried out mainly by using psychophysical evaluation methods.[3,4] With the recent rapid developments in motion image technology, there has been, therefore, an increasing need to carry out studies using more precise, objective evaluation methods in regard to human vision and motion images. In this respect, there has been a report of a quantitative evaluation of image quality using the human electroencephalogram (EEG).[7] According to this report, the average EEG power in the alpha-wave frequency band was significantly greater when viewing HD motion images than when viewing NTSC (720 × 480 pixels) images, especially for natural scenes.[7] Although studies using the EEG were found to be useful for the evaluation of image quality, they have not been subsequently applied in studies to investigate differences in image quality with different frame rates.

Therefore, with a view to the practical application of high frame rates in future standardizations of image technology, the objective of the present study is to investigate the effects of motion image stimuli with normal [60 frames/s (fps)] and high frame rates (240 fps) on EEG power spectra and to compare them with those obtained with real (continuous) motion stimuli.

2 Background of research on motion image technologies with high frame rate

We have previously reported that high frame rate is an effective solution for the problem of degradation of the quality of motion images, such as motion blur and jerkiness.[3] Furthermore, other investigators have also reported on experimental[4] and analytical studies using spatial frequency responses[5] with regard to the relationship between frame rates and image quality. These studies provide important guidelines for the target of development of the next generation image technologies.

The human eye with a visual acuity of 1.0 is capable of resolving 1 min of visual angle, which corresponds to about 1 pixel in an HD image in the standard viewing condition, that is, at three times the distance of the screen height. Therefore, with still images, the ability of the viewer to resolve a scene is not made to become poorer by HD pixelation. However, in the case of moving HD images, with 60 fps frame rate, commonly, the viewer is significantly less able to resolve a reproduced scene than when viewing the original moving scene directly. This is due to the use of certain devices in the reproduction which cause blur, such as hold-type displays

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that give rise to "retinal slip" and cameras with long shutter times. This indicates that the portrayal of motion with conventional film or video leaves significant room for improvement. Prior to the present study, therefore, experimental investigations for determining the required frame rate were carried out.[3] It was found that the limits of perception for both blur and jerkiness exist near 250 fps. Because little differences in the perception were seen at frame rates above 250 fps, this frame rate was thought to be suitable as the target specification in constructing visual equipment.[3] Furthermore, in consideration of the frame rates of 24 fps in cinema and 60 fps in video, 240 fps was thought to be the desirable choice of frame rate for countries with 60 fps video because it is a simple multiple of those frame rates.

3 Experimental methods and setup

From the foregoing considerations about frame rates, we chose 60 and 240 fps motion images as stimuli for objective evaluation experiments with EEG measurements that are described in the following.

3.1 Stimulus presentation and experimental setup

(1) Method of stimulus presentation

In order to avoid any pictorial cues, and to make the experimental results clearer, a simple rectangular image, which is moved horizontally across the screen, was used as the stimulus. The specifications such as size, position, and luminance are shown in Fig. 1. The color of the stimulus and the background is neutral and the luminance of the background was 0.53 cd/m^2. The stimulus speed in each direction, which was 2 pixels/frame (240 fps) count in the present experiment, was chosen to be within the range in which normal smooth pursuit viewing is possible.

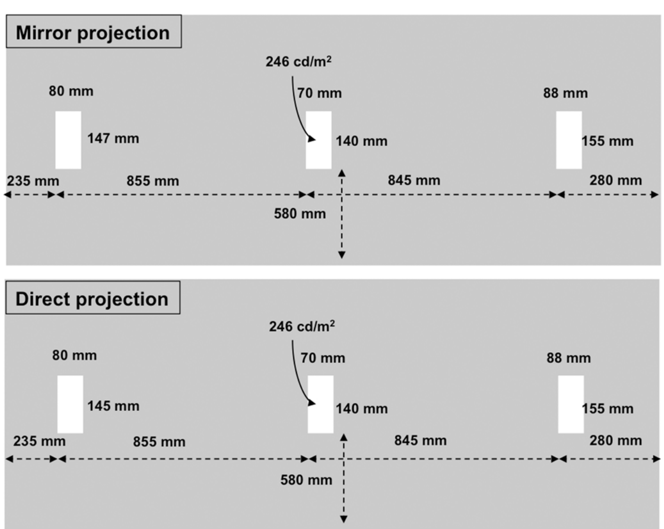

FIGURE 1 — Outline of rectangular image presentation. The dimensions for real motion image (Stimulus-N: upper part) and 60/240 fps motion image stimuli (Stimulus-60FPS/Stimulus-240FPS: lower part) at the positions of center, left-end, and right-end of the screen are shown. The luminance values at the central position are also given.

In order to make a comparative study by EEG analyses of the similarity of the visual effects of a 60 fps stimulus (stimulus-60FPS) and of a 240 fps stimulus (stimulus-240FPS) to those of a real (continuous) motion stimulus (stimulus-N), stimuli were presented by two different methods. As shown in Fig. 1, motion image stimuli, at 60 and 240 fps, of the rectangular figure undergoing horizontal translation were prepared. In addition, as a reference, a stimulus image undergoing continuous horizontal back-and-forth motion (made to be a real translating stimulus similar to a natural image) was produced from a still image corresponding to a single frame of the motion image. For this purpose, the light from the projector was reflected by a servo-controlled mirror that performs a back-and-forth rotational motion.

In order to confirm the congruity of the motions of these displayed images, we plotted the measured positions of the images presented by the mirror and multi-frame methods of display (indicated, respectively, as the mirror and projected motions in Fig. 2) at different frame counts. In this measurement, only the stimulus-240FPS was examined because the motions of the stimulus-60FPS and stimulus-240FPS displays are nearly the same. The method of measurement was to capture the translating displays of stimulus-N and of stimulus-240FPS with a home HD recording camera and to obtain their horizontal positions from the images using original image processing software. As a result, it was confirmed, as shown in Fig. 2, that the translation movements of the images displayed by the mirror and by the multi-frame methods were fully matched in the central position of the horizontal back-and-forth movement, that is, the point of fixation at the center of the screen (to be described in the following).

(2) Outline of experimental setup

Figure 3 is a schematic diagram of the whole experimental setup used in the present study. A transmissive (rear-projection)

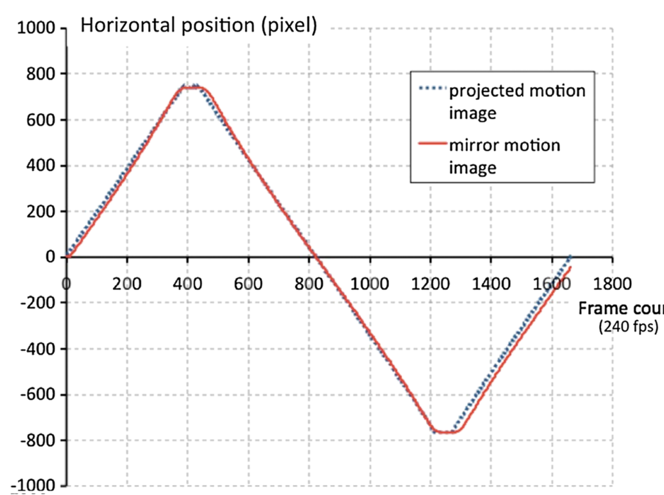

FIGURE 2 — Tracking accuracy between the mirror and the frame-image presentation. See text for further explanation.

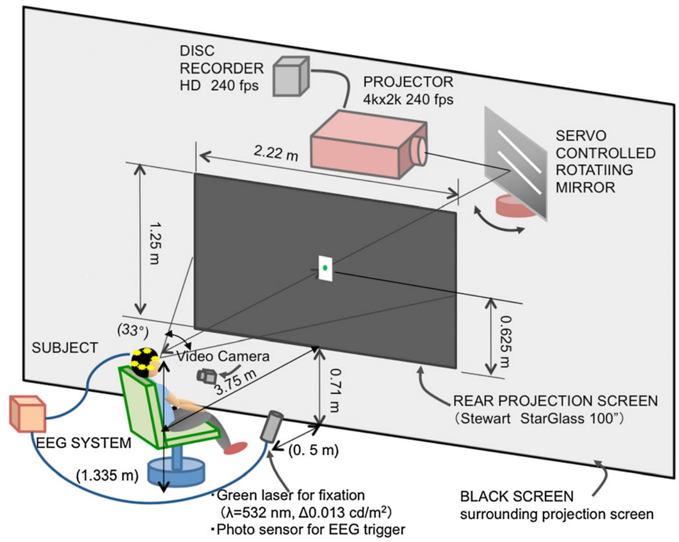

FIGURE 3 — Outline of experimental setup system for the investigation of motion image stimuli. See text for further details.

screen having a height of 1.25 m and a width of 2.22 m, indicated by the dark gray color in the center of Fig. 3, was used for display. This screen is used to present, centered about its center, stimulus-N, stimulus-60FPS, and stimulus-240FPS undergoing horizontal back-and-forth motion as previously described. The bottom of this screen was 0.71 m above the floor. In order to exclude interference by light which is not necessary for the subject, the screen was surrounded by blackout screens of black cloth (indicated by the light gray area in Fig. 3), extending 1.5 m on each of the left and right sides as well as 1 m above and 0.71 m below it. A 4k × 2k (4096 × 2160 pixels) 240 fps projector and a servo-controlled mirror capable of rotational motion were placed behind the screen.

Video data were supplied to the projector by an HD 240 fps disc recorder with an HD (1920 × 1080 pixels) resolution. The subject was requested to be seated in front of the screen in a relaxed sitting position, and the height of the chair and its distance from the screen were adjusted so that the distance from the surface of the screen to the eyes was 3.75 m and that they were at the same height (1.335 m above the floor) as the center of the screen.

An SXRD model SRX-110 projector, manufactured by Sony Corporation, Japan, was modified to enable its use for both stimulus-60FPS and stimulus-240fps. This is a fully hold-type line-sequential reflective liquid crystal display (LCD) projector with 4096 × 2160 pixels and the capability for up-converted display of HD images by two times in width and height by modified linear interpolation. The display is driven by the method of dividing the screen into four quadrants. In the upper right quadrant, pixels are refreshed line by line (horizontal) from bottom to top and from left to right in each line. In the upper left quadrant, the refresh sequence is with mirror symmetry to the upper right quadrant about the vertical midline. In the lower quadrants, the sequence is with mirror symmetry to the upper quadrants about the horizontal midline. The sequences in all quadrants are synchronized to start from the center of the screen at the same time. The driving operation is always at 240 fps, with presentation of images at 60 fps realized by producing identical images in identical positions for four consecutive frames. The rotating mirror system was custom-built.

During the experiment, the subject was asked to keep gazing at the point of fixation at the center of the screen. Laser light was used to indicate the point of fixation, irradiating it upward at an angle toward the screen from below and in front of the screen. Further, the luminance of the laser light was sufficiently reduced by an ND filter in order to minimize the visual effects on the subject. A green laser [JPM-1-3(A4) APC, 3 V, 0.6 mW] was used with an ND filter of optical density 2.0. The luminance at the viewing position was 0.013 cd/m^2 as the difference in luminance with the laser light on and off.

Experiments were conducted in an air-conditioned (about 23 °C of room temperature) dark room. In order to confirm the absence of significant eye movements of the subjects during the experiments in the dark room, a home HD recording camera with infrared capture capability was placed below the screen (see Fig. 3). In addition, in order to identify the timing of the presentation of stimuli during the EEG recording which will be described in the next section, a custom-built photo sensor unit using a phototransistor was used to detect the point in time at which the stimulus image passes the point of fixation and mark it automatically on the EEG recording.

3.2 Subjects and experimental/analytical methods

The present experiment was conducted with the approval of the Ethics Committee of Showa University School of Medicine (Date of approval: September 27, 2012; Application Number 1298; Subject: "Study to evaluate the biological effects of high frame rate images"). Subjects were recruited by a detailed description of such matters as the purpose and procedure of the experiment, and 10 healthy adult participants whose consent was obtained [eight men (ages 21–30 years) and two women (ages 19 and 24 years) of overall average age 23.3 ± 2.9 years (standard deviation (SD)] were enlisted.

Tests using an auto ref/keratometer (NIDEK ARK530A) and ophthalmological examinations were carried out in the Department of Ophthalmology, Showa University Hospital on the subjects participating in the experiment, and the absence of any ophthalmological abnormality such as of eye position or acuity was confirmed in each subject. In addition, the absence of any abnormality with regard to blood pressure was confirmed by measurements before and after the experiment. By monitoring the eye movements of the subjects during the experiment using the home HD recording camera described in the foregoing, it was confirmed that the subjects were fixating properly.

Each subject was asked to perform the following preliminary test of visual perception in a dark room visual environment before EEG measurement. That is, it was confirmed that differences of motion picture quality in terms of both blur and jerkiness could be recognized, by presenting 240 and 60 fps video clips with significant blur due to capture with an open shutter and 60 fps video clips with significant jerkiness due to capture with a shutter speed of 1/240 s. It was also confirmed that normal binocular viewing was possible by presenting stereoscopic video clips.

A model CM-E (sampling frequency of digital output signal: 400 Hz) instrument manufactured by Astro-Med, Inc., USA was used to measure the EEG. Flat-type electrodes were used with conductive gel and all electrode impedances were below 5 kΩ. The loci measured were left and right occipitals: O1, O2 by the 10–20 system of electrode placement,[8] presuming responses in the vicinity of the primary visual cortex.

The left and right auriculars: A1, A2; midline central: Cz; and midline front polar: Fpz loci were used as reference electrodes, and the measured data were obtained at ipsilateral loci, that is, O1 with respect to A1 and O2 with respect to A2, respectively (hereinafter indicated as A1-O1 and A2-O2).

Stimulus-N, stimulus-60FPS, and stimulus-240FPS were presented in a predetermined common random order for all subjects in which each was presented three times, and two EEG epochs for A1-O1 and A2-O2 were recorded with the stimulus moving in each direction. Therefore, a total of 12 EEG epochs were obtained for each subject. The entire EEG data were acquired continuously during the period of presentation.

During the EEG recording, as previously described, the point in time at which the image stimulus passed the point of fixation was detected using the photo sensor placed at that position and a mark was made on the EEG recording. These EEG data and the timing signal for displaying the stimulus were acquired by a conventional PC connected to the EEG instrument, and fast Fourier transform (FFT) analysis was performed off-line after completion of the measurement to obtain the power spectrum. Commercially available calculation software (MATHEMATICA) was used for computation of the FFT and the power spectrum.

The EEG used for the analysis comprises a total of 512 sampling counts centered about the point in time when the leading edge of the translating rectangular image passed the point of fixation. That is, the duration of this range is 512/400 = 1.28 s and the average speed of the stimulus during this time is 452.9 HD pixel/s from the results shown in Fig. 2, and the visual angle corresponds to ±290 HD pixels, that is, ±5.1°.

Of the data of the 10 subjects, those two subjects in which irregularities in the form of bursts were found were excluded from analysis.

In each subject, such recordings for both A1-O1 and A2-O2 were made three times with the stimulus moving in each direction, and FFT analysis was applied to obtain the average power spectrum for each type of stimulus presented, stimulus-N, stimulus-60FPS, and stimulus-240FPS.

The similarity of the EEG power spectral patterns in response to image stimuli was analyzed in this study by adopting the Canberra distance[9] ($\mathrm{CD}[\boldsymbol{u}, \boldsymbol{v}]$), which is a commonly used measure to evaluate similarity between the spectral patterns. This measure is defined as

$$\mathrm{CD}[\boldsymbol{u}, \boldsymbol{v}] = {}_{i} |u_i - v_i| / {}_{i} (|u_i| + |v_i|),$$

where $\boldsymbol{u}$ and $\boldsymbol{v}$ are the vector data of the power spectra with u_i and v_i denoting the ith elements of the vectors. Averages were calculated of distances in the cases of both A1-O1 and A2-O2 recordings and of both stimulus directions and for the full cohort of eight subjects.

4 Results

Figure 4(a–c) shows examples of the EEG recordings at A1-O1 obtained in one subject during image stimulation, (a) stimulus-N, (b) stimulus-60FPS, and (c) stimulus-240FPS. The stimulus was moving from left to right in these examples. Figure 5 shows the results of averaging the power spectra obtained during three times of presentation in the same subject and for the same condition as in Fig. 4 under stimulus conditions of (a) stimulus-N, (b) stimulus-60FPS, and (c) stimulus-240FPS. Here, the abscissa in Fig. 4 corresponds to time (indicated in sampling counts) and the ordinate is the signal level of the EEG (μV), whereas the abscissa and the ordinate in Fig. 5 are frequency [Hz] and level of power [μV^2], respectively. Figure 6 shows the average power spectra under stimulus conditions of (a) stimulus-N, (b) stimulus-60FPS, and (c) stimulus-240FPS for all eight subjects. Here, the averages are taken with each subject for the three presentations including the cases of both A1-O1 and A2-O2 recordings and of both stimulus directions.

Figure 7 shows the results of calculating the average Canberra distances, in the cases of both A1-O1 and A2-O2 recordings and of both stimulus directions and for the full cohort of eight subjects, between the average EEG power spectral patterns in the case of the stimulus-60FPS or of the stimulus-240FPS and those in the case of the stimulus-N. The value of the Canberra distance between the cases of stimulus-240FPS and stimulus-N [82.6 ± 1.20 (mean ± SE)] was significantly less than that between the cases of stimulus-60FPS and stimulus-N (91.7 ± 3.86), (t-test, $t = 2.258$; $p = 0.0299$), indicating that the perception of motion image with higher frame rate would be closer to that of the real motion image. The comparatively large standard error for the latter case could indicate the presence of greater variability among the responses of individual subjects when viewing artificial motion images that are less close to real images.

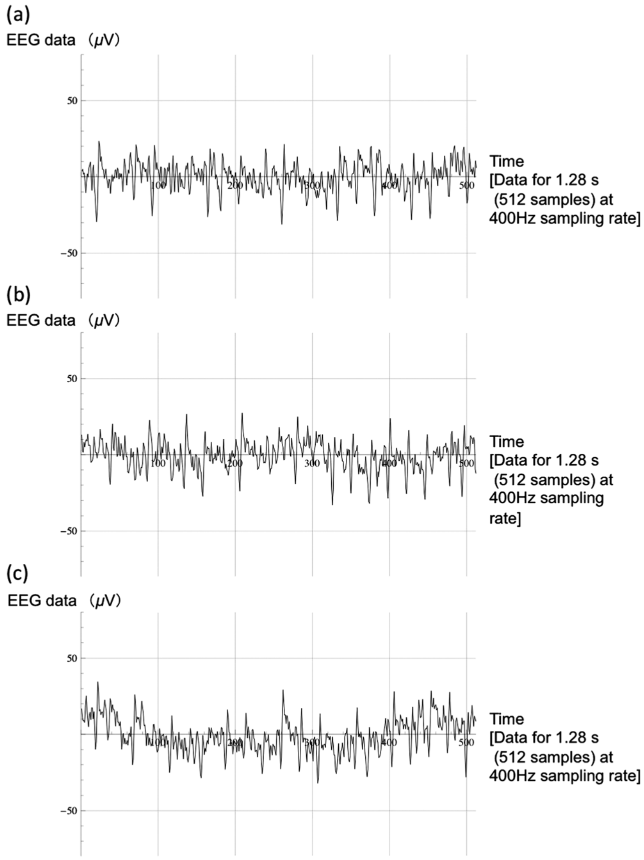

FIGURE 4 — Examples of the EEG recordings at A1-O1 obtained in a subject during image stimulation, (a) stimulus-N, (b) stimulus-60FPS, and (c) stimulus-240FPS. [Correction added on December 18, 2014, after first online publication: axis labels added.]

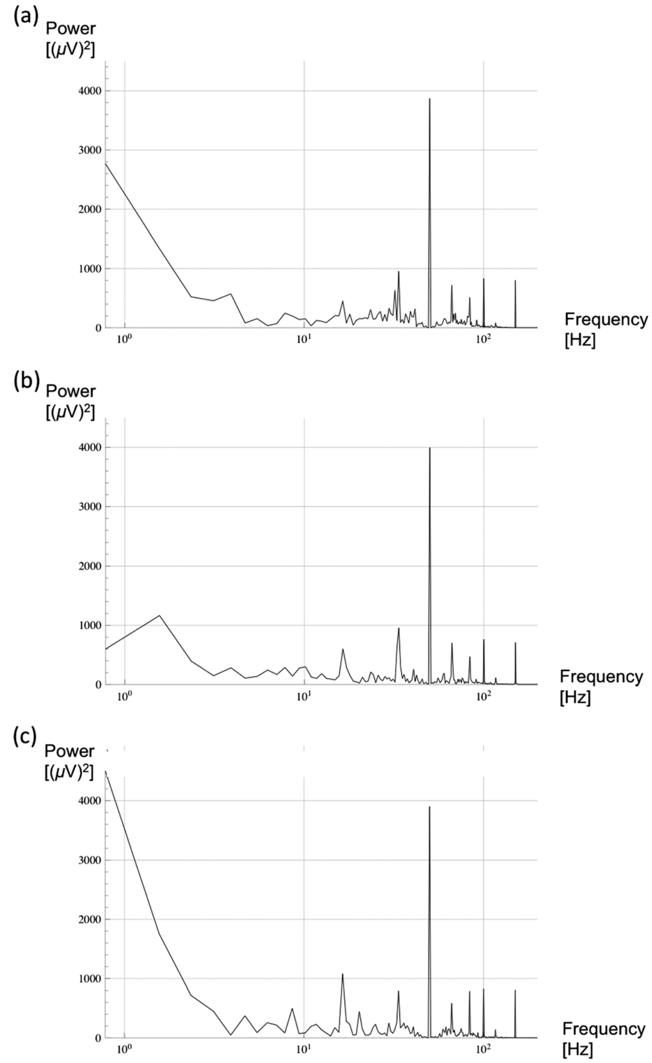

FIGURE 5 — Averaged power spectral results obtained in the same subject as in Fig. 6 under stimulus conditions of (a) stimulus-N, (b) stimulus-60FPS, and (c)stimulus-240FPS. [Correction added on December 18, 2014, after first online publication: axis labels added.]

Figure 8 shows the results of calculating the Canberra distances, for the cases studied in Fig. 7, for different EEG bands.[10] The bands are (a) delta [0.1–3.5 Hz], (b) theta [4.0–7.5 Hz], (c) alpha [8.0–13 Hz], (d) beta [14–30 Hz], (e) gamma [30–100 Hz], and (f) above gamma [100–200 Hz]. A smaller value of the Canberra distance between the spectra in the cases of stimulus-240FPS and stimulus-N than that in the cases of stimulus-60FPS and stimulus-N, as was found in Fig. 7 for complete spectra, was also found for each band. The difference in the Canberra distances between the two conditions was large for the above gamma (t-test, $t = 2.623$, $p = 0.0117$) band, moderate for the delta (t-test, $t = 1.646$; $p = 0.1048$) and gamma (t-test, $t = 1.267$; $p = 0.2137$) bands and small for the alpha (t-test, $t = 0.775$; $p = 0.4415$), beta (t-test, $t = 0.715$; $p = 0.4790$), and theta (t-test, $t = 0.642$; $p = 0.5231$) bands.

5 Discussion

The results obtained in the present experiments clearly indicate that the occipital EEG responses, which originate mainly from the vicinity of the primary visual cortex, following the image stimuli with stimulus-240FPS are closer to that with stimulus-N as compared with that with stimulus-60FPS. This strongly suggests that image stimuli with higher frame rate results in cerebral activity that more closely resembles the activity when viewing natural scenes compared with the response to the conventionally used frame rate.

In this study, the EEG waveforms measured in all subjects were analyzed by FFT to obtain the power spectrum, not by direct integration. This approach was adopted in regard to the following considerations. If the average is taken directly from a large number of EEG waveform data, although characterization of the waveform comprising the low frequency components of the EEG may be obtained, it is difficult to extract the essential characteristics of the EEG that has high frequency components on the order of the frame rates of 60–240 Hz. Direct EEG integration causes these important frequency components to become lost because they do not appear in synchrony from one measurement to another after the onset of image stimulation. This is due to the variability

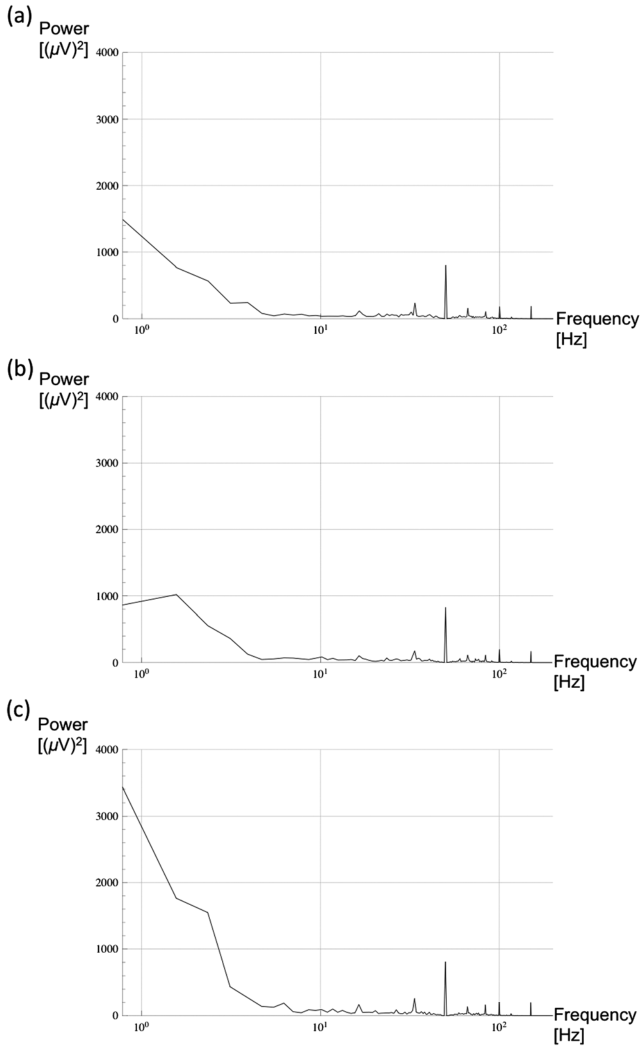

FIGURE 6 — Average power spectra under stimulus conditions of (a) stimulus-N, (b) stimulus-60FPS, and (c) stimulus-240FPS for all eight subjects. The averages are taken with each subject for the three presentations including the cases of both A1-O1 and A2-O2 recordings and of both stimulus directions. [Correction added on December 18, 2014, after first online publication: axis labels added.]

both among different subjects and within subjects following the physical stimulus on the retina, and this variability is caused by differences of pupil diameters and of the state of neural activity at the time of image stimulation. It is therefore inappropriate to evaluate the EEG waveforms by simple averaging. The average of EEG power spectra used in this study would be much less dependent on such variability and extracts the important high frequency components. These are the same considerations as those that are important in event-related spectral perturbation,[11] of which the present experiment may be regarded as a case with a single latency.

We evaluated the differences in the EEG power spectral patterns between the cases of stimulus-60FPS and stimulus-240FPS as compared with those in the case of stimulus-N using an index of Canberra distance and found that the spectral pattern of stimulus-240FPS was much more similar to that of stimulus-N. This means that the present experiments

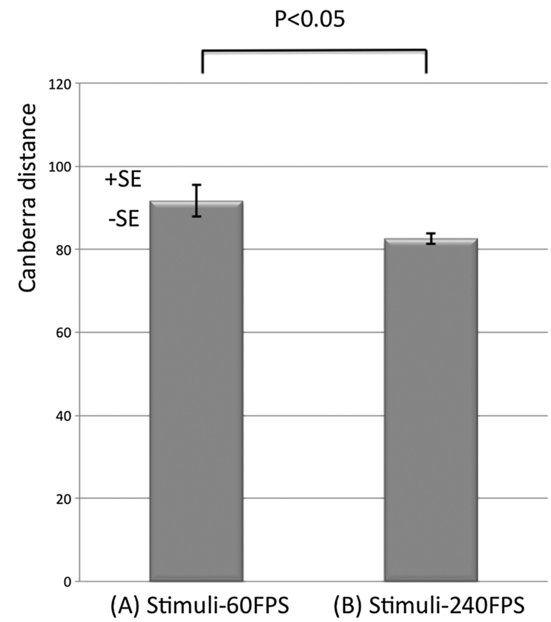

FIGURE 7 — Canberra distances of the EEG power spectral patterns between stimulus-60FPS and stimulus-N (A), and between stimulus-240FPS and stimulus-N (B). The error bars in this graph indicate standard errors (±SE) obtained for eight subjects. See text for further explanation.

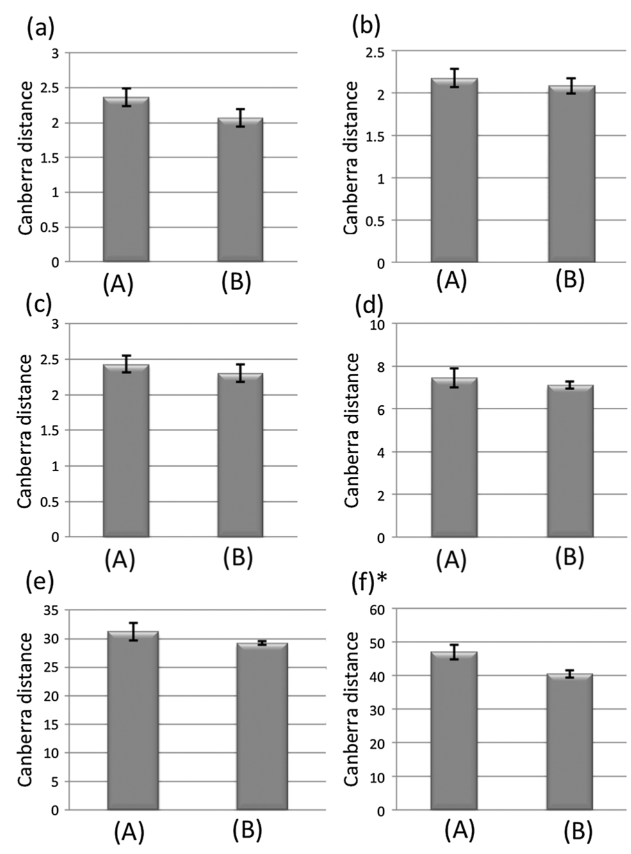

FIGURE 8 — Canberra distances of the EEG power spectral patterns between stimulus-60FPS and stimulus-N (A), and between stimulus-240FPS and stimulus-N (B), by different bands: (a) delta, (b) theta, (c) alpha, (d) beta, (e) gamma, and (f) above gamma. The error bars in this figure indicate standard errors (±SE) obtained for eight subjects. See text for further explanation. The asterisk indicates that there is a significant difference in the distances.

address the question of which of the two image stimuli resembles more closely the real translating stimulus in terms of the response of brain activity.

It is well known that significant artifacts are commonly observed in EEG waveforms due mainly to contact impedance fluctuations between the electrodes and the scalp. In order to avoid dominant effects due to such artifacts, the Canberra distance, which has higher sensitivity for values close to null spectral power, was used as the distance metric in the present study. In our previous study, we also found a similar difference in the EEG power spectral patterns by using a general metric, the correlation distance.[12] However, this metric has relatively high sensitivity to artifacts having statistical outliers. In fact, p-values in t-tests showed $p = 0.0372$ for the correlation distance and $p = 0.0299$ for the Canberra distance, indicating a more distinctly significant difference with the use of Canberra distance.

Other possible sources of artifacts are electrical fields from facial muscle electromyographic activity and false electrical signals that can contaminate the EEG. The small or moderate difference in the Canberra distances that was found between the two conditions in Fig. 8 for the beta and gamma bands indicates that electromyographic activity, which would appear mostly in these bands,[13] is not the origin of the difference in distances in Fig. 7. The signal due to power line interference was filtered out in the EEG measurement, and by cancelation, no other significant persistent false components would have remained after the calculation of distances.

In our previous studies, it was found that human perception of motion image quality is capable of discerning differences among images with different frame rates up to about 240 Hz.[3] Therefore, it may be expected that there are differences in the EEG when a subject views images with different frame rates in this range. This would be possible from the viewpoint of the elementary neural response that has a refractory period of about 1 ms.[14] In the present experiment, in consideration of the significant 60 and 240 Hz components of the stimuli, it is expected that the visual information from the retina is reflected in the occipital EEG waveforms in the gamma and higher frequency EEG bands. These effects may, in turn, give rise to changes in activity in other, "indirect," frequency bands. Differences in such effects between the cases of stimulus-240FPS and of stimulus-60FPS may be expected to be present. Because the stimulus-240FPS is more similar to that of continuous translation than the stimulus-60FPS, the effects would result in specific neural activity that is closer to that with stimulus-N. A subtle difference was found in the Canberra distances between the two conditions in Fig. 8 for the gamma band. Substantial "indirect" effects were indeed also observed because significant differences were found in the Canberra distances between the two conditions in Fig. 8 for the above gamma bands. This finding is suggestive in view of the recent observations of correlations between high-gamma band ECG activity and neuronal activation.[15]

6 Conclusion

The power spectral characteristics of the EEG in the case of a translating image stimulus at 240 fps were found to be closer to those in the case of a real translating image stimulus than to those in the case of a stimulus at 60 fps. It could be considered that motion images with a high frame rate results in human brain activity that is closer to that in the state of viewing a natural scene. It appears that, consequently, the viewer is able to have a perception of motion image quality that is closer to the impression when viewing a natural scene.

Greater spatial, temporal, and color resolutions are required for displays with capabilities approaching the limits of perception of human viewers. In view of the rapid advancement in image technologies, further investigations focusing on physiological functions of perception in human vision will be needed toward the realization of much higher quality motion images.

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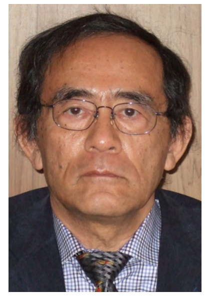

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