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Threshold Determination Criterion in Steady-State Visual Evoked Potential-Based Acuity Assessment: A Comparison of Four Common Methods

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ABSTRACT The steady-state visual evoked potential (SSVEP) visual acuity is usually defined by extrapolating a straight line regressed through significant SSVEP amplitudes plotted versus spatial frequencies to 0 μV or a noise level floor, or the finest spatial frequency evoking a significant SSVEP. This study aimed to compare the performance of the commonly used threshold determination criteria of the extrapolation technique and the finest spatial frequency technique. Visual acuity was measured both by the Freiburg Visual Acuity Test (FrACT) and SSVEP with vertical sinusoidal reversal gratings in ten adults. The extrapolation technique including three methods of linear extrapolation to zero (C_1), linear extrapolation to noise level baseline (C_2) and linear extrapolation to zero versus log spatial frequency (C_3), and the finest spatial frequency technique with significance determination by canonical correlation analysis (CCA) and "OR" operation (C_4) were used to determine the SSVEP visual acuity. Bland–Altman method found a pretty good agreement between the SSVEP and FrACT acuity obtained by all the four threshold estimation criteria. One-way repeated-measures ANOVA and Bonferroni *post-hoc* analysis found that there was no significant difference among visual acuities measured by FrACT and all the four criteria, except for the visual acuity estimated by C_1 slightly higher than that of C_2, demonstrating that these visual acuity estimating methods had a similar performance in evaluating the visual function. The correlation and agreement between subjective FrACT acuity and objective SSVEP acuity measured by four criteria respectively were all pretty good, demonstrating that all of these four threshold estimation criteria had a good performance in SSVEP visual acuity assessment.

INDEX TERMS Steady-state visual evoked potential (SSVEP), visual acuity, threshold determination, spatial frequency.

I. INTRODUCTION

At least 2.2 billion people suffer from a vision impairment or blindness in our world with most as a result of uncorrected refractive errors and cataracts, according to the World Health Organization [1]–[3]. As one of the most critical parts of the diagnosis of visual disorders, visual acuity testing is traditionally based on psychophysical methods, such as the naming of Snellen letters. These tests require examinees to have adequate cognitive and communication abilities and are difficult for little children and even the mentally disabled or malingerers [4], [5].

Visual evoked potentials (VEPs) offer an optional method to assess visual acuity objectively in people with difficulties in perception and recognition, and this technique of VEP-based visual acuity assessment has been studied for about

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40 years [6]–[8]. Recently, the steady-state VEPs (SSVEPs), combining the characteristics of quickness and high fault tolerance, have become the most widely used technique for objective visual acuity measurement [9]–[11]. By sweeping the spatial frequency of the visual stimulus, the SSVEP acuity is correlated to the maximum observable spatial frequency of stimulus with a significant SSVEP response.

The commonly used techniques of SSVEP acuity contain several parts of the visual stimulus and its sequencing, the SSVEP acquisition and analysis, and the SSVEP acuity threshold determination [8], [12]. Previous studies have explored the effects of different parameters of visual stimuli, such as the temporal frequency [13], luminance [14], contrast [15], stimulus pattern [9], [16], spatial frequency properties, and some sweep parameters [13], [17], [18], and recommended their relevant parameter settings [8], [12], [19]. The acquired SSVEPs are usually analyzed in the frequency-domain by discrete Fourier transform (DFT).

As for the SSVEP acuity threshold definition, the point at which the SSVEP response emerges or disappears significantly is defined as the threshold of SSVEP visual acuity [20], [21]. The most commonly used method is the extrapolation technique, which defines the SSVEP acuity by extrapolating a straight line regressed from the highest SSVEP amplitude response plotted versus spatial frequency to the baseline of 0 μV or a noise level [12], [22], [23], and the critical spatial frequency corresponding to the intersection with the baseline is determined as the SSVEP acuity [24]. Another alternative strategy for defining the SSVEP acuity is called the finest spatial frequency technique [12], also named as the smallest check size technique [25], which defines the SSVEP acuity as the finest spatial frequency evoking a significant SSVEP [26]–[28], where the significance of the SSVEP response to the stimulus is usually determined by the signal-to-noise-ratio (SNR) [29], [30]. The phase, tending to lag gradually across finer spatial frequencies, sometimes has also been employed for signal detection alongside the SNR criterion [8]. However, although all of these SSVEP acuity threshold definition criteria were used well in the previous studies, no study has compared the performance of these commonly used threshold definition techniques in the same subjects [8].

For these reasons, in this study, we aimed to compare the performance of the commonly used threshold determination criteria, i.e., the extrapolation technique including three methods of linear extrapolation to zero, linear extrapolation to noise level baseline, and linear extrapolation to zero versus log spatial frequency [8], [12], and the finest spatial frequency technique with significance determination by canonical correlation analysis (CCA) and "OR" operation [28], in the SSVEP acuity assessment.

II. METHODS

A. PARTICIPANTS

Each subject was asked to sign an informed written consent following a protocol approved by the institutional review board of Xi'an Jiaotong University and conformed to the Declaration of Helsinki. Ten healthy postgraduate students (two females) in Xi'an Jiaotong University, with an age range of 21-27 years, participated in this experiment. Other than myopia, no subjects had any eye disease. The subjective psychophysical visual acuity without any refractive correction, ranging from −0.10 to 0.90 logMAR, was evaluated monocularly by the Freiburg Visual Acuity Test (FrACT) [31], as shown in Table 1.

TABLE 1. Clinical details of all subjects. Visual acuity is expressed in logMAR.

Subject No.	Age	Gender	OD	OS
S1	21	Male	0.00	0.07
S2	21	Male	0.39	--
S3	24	Female	0.34	--
S4	27	Male	-0.10	--
S5	25	Male	0.92	0.86
S6	23	Male	0.06	--
S7	23	Male	-0.05	-0.09
S8	24	Male	0.23	--
S9	25	Male	0.64	--
S10	24	Female	0.02	0.07

B. VISUAL STIMULI

We used the vertical sinusoidal gratings as the visual stimuli, displayed at a rate of 3.75 Hz or 7.5 reversals per second (rps). A 24.5-inch LCD monitor (PG258Q, ASUS, Taipei, China) with a high refresh rate of 240 Hz and a resolution of 1920 (horizontal)∗1080 (vertical) pixels was used to present the stimuli. Before the experiment, a color correction instrument (Spyder 5 Elite, Lawrenceville, United States) was used to calibrate the monitor, and a luminance meter (SAMPO SM208, Shenzhen, China) was used to detect the luminance of the pattern. The Michelson contrast of the visual stimuli was 40%, and the mean background luminance was 80 cd/m^2. The visual stimuli were generated by MATLAB (MathWorks, Natick, USA) with the Psychophysics Toolbox [32].

The visual angle of the entire stimulus pattern was set as 4 degrees by adjusting the stimuli size and viewing distance. The eleven spatial frequencies of the vertical sinusoidal gratings were in logarithmically equidistant steps corresponding to the optotypes from 1.0 logMAR, 0.9 logMAR,..., 0.0 logMAR [9], [28], resulting in the spatial frequencies as follows: 3.0, 3.8, 4.8, 6.0, 7.5, 9.5, 12.0, 15.0, 19.0, 23.8, and 30.0 cycles per degree (cpd). There were five trials in each spatial frequency step and one trial lasted 5 s with an interval of 2 s between two trials. Subjects were instructed to monocularly maintain the red fixation cross at the center of the visual stimulus during the experiment [9].

C. DATA ACQUISITION AND PROCESSING

In this study, electroencephalography (EEG) signals were collected by a g.USBamp EEG amplifier and a g.GAMMAbox active electrode system (g.tec, Schiedlberg, Austria) at a sampling frequency of 1200 Hz. According to the international 10-20 electrode system and the ISCEV standard [33], [34], six active electrodes (PO3, PO4, POz, O1, O2, and Oz) were used to record the EEG signals with a reference electrode A1 at the left earlobe and a ground electrode at the forehead [9]. Besides, an online band-pass filter between 2 to 100 Hz and a notch filter between 48 and 52 Hz were used to remove artifacts and power line interference.

D. SSVEP SIGNAL ANALYSIS

1) PRE-PROCESSING OF EEG DATA

A band-pass filter between 3 to 40 Hz was utilized to eliminate the high-frequency interferences and low-frequency drifts of EEG signals. The five trials in one spatial frequency step were averaged to a 5-s data epoch for the next signal processing. Taking into account a time latency in the visual system, the first 0.2-s data were removed for each EEG data epoch [35].

2) DISCRETE FOURIER TRANSFORM (DFT)

Common average reference (CAR) fusion is commonly used in EEG spatial filtering by subtracting the mean of all electrode signals from the selected electrode signals to enhance the SNR of the selected electrode signals [36]. In this study, we chose the Oz electrode in spectral analysis, so the time-domain EEG signals V_i for each epoch to be analyzed can be expressed as

$$\mathrm{V_i} = \mathrm{V_{Oz}} - \frac{1}{6}\sum\nolimits_{\mathrm{j}=1}^{6} \mathrm{V_j}. \tag{1}$$

where V_j is the EEG signals from six electrode channels (PO3, PO4, POz, O1, O2, and Oz).

Then, each epoch was analyzed using DFT, and the magnitude at the target frequency of 7.5 Hz was regarded as the SSVEP amplitude. Next, the noise was determined by the mean amplitude at the two frequencies of 6.5 and 8.5 Hz on either side of the target frequency [23], [29], [30]. Hence, the SNR can be defined as the ratio of SSVEP amplitude to noise, which we called it $\mathrm{SNR_0}$.

3) CANONICAL CORRELATION ANALYSIS (CCA)

Another method in SSVEP analysis was CCA [37], [38], which was described in our previous studies [9], [28]. Here, CCA was used to calculate the correlations between the six-channel EEG signals X and the reference signals Yi. X is the average EEG signals of five trials in one spatial frequency step. The reference signals Yi are constructed at the reference frequency fi ($i = 1, 2 \ldots, N$):

$$\mathrm{Y_i} = \begin{pmatrix} \sin(2\pi \mathrm{f_i t}) \\ \cos(2\pi \mathrm{f_i t}) \end{pmatrix}, \quad \mathrm{t} = \frac{1}{\mathrm{F_s}}, \ldots, \frac{\mathrm{S}}{\mathrm{F_s}} \tag{2}$$

where F_s is the sampling rate, and S is the sample points. Here, the reference frequency f_i is set to 1.0, 1.1..., 20.0 Hz (i.e., $N = 191$).

The linear transformations of X and Y_i are $x = w_x^T X$ and $y_i = w_{yi}^T Y_i$, respectively, and the maximum correlation coefficient value ρ_i between X and Y_i can be calculated by the CCA method as

$$\rho_i = max_{w_x, w_y} \frac{E[w_x^T X Y_i{}^T w_{yi}]}{\sqrt{E\left[w_x^T X X^T w_x\right] E[w_{yi}^T Y_i Y_i^T w_{yi}]}}. \tag{3}$$

The maximum correlation coefficient value ρ_i, representing the maximum correlation between X and Y_i, can be regarded as the response to the SSVEPs at the reference frequency f_i ($f_1, f_2 \ldots, f_N$). Therefore, all the ρ_i and their corresponding frequency f_i can be plotted as a CCA spectrum. The ρ_i at the stimulus frequency of 7.5 Hz was regarded as the SSVEP amplitude.

The SNR for CCA, which we called $\mathrm{SNR_1}$, was defined as the ratio of the square of the CCA coefficient at the stimulus frequency of 7.5 Hz to the mean value of the square of the n adjacent points on the CCA spectrum [9], [38]:

$$SNR_1 = \frac{z(f)^2}{\frac{1}{n} * \sum_{k=1}^{\frac{n}{2}} \left[z(f + c*k)^2 + z(f - c*k)^2\right]}. \tag{4}$$

where n is set to 10, and f is 7.5 Hz. $z(f)$ is the CCA coefficient of the stimulus frequency f on the CCA spectrum. Then c, which is set to 0.1, is the scale value of abscissa on the CCA spectrum.

E. THRESHOLD ESTIMATION CRITERIA

C_1 (Linear Extrapolation to Zero): The most used method to define the SSVEP visual acuity is by extrapolating a regression line from the last significant SSVEP peak to 0 μV between significant SSVEP amplitudes and spatial frequencies [8], [12]. Here, the range for the regression line fit was defined as the data between the last signal peak with an $\mathrm{SNR_0} \geq 3$ and the last data point with an $\mathrm{SNR_0} \geq 1$ [8], [23]. The spatial frequency of the intercept corresponding to the X-axis, i.e., 0 μV baseline, was defined as the SSVEP threshold of visual acuity.

C_2 (Linear Extrapolation to Noise Level Baseline): Compared to $\mathrm{C_1}$, the extrapolation in $\mathrm{C_2}$ was from the last SSVEP peak to the noise level baseline against spatial frequency [22]. The noise level baseline was calculated by averaging the EEG noise of the eleven spatial frequency steps for each individual [29]. The range for the regression line fit was also defined as the data between the last signal peak with an $\mathrm{SNR_0} \geq 3$ and the last data point with an $\mathrm{SNR_0} \geq 1$ [23]. The spatial frequency of the intersection with the noise level baseline was determined as the SSVEP threshold of visual acuity.

C_3 (Linear Extrapolation to Zero Versus Log Spatial Frequency): Compared to $\mathrm{C_1}$ and $\mathrm{C_2}$, the extrapolation in $\mathrm{C_3}$ was from the last SSVEP peak to the 0 μV baseline against the log spatial frequency [18, 39]. The regression range and the definition of SSVEP acuity were the same as $\mathrm{C_1}$.

C_4 (Finest Spatial Frequency Evoking a Significant SSVEP): According to our previous studies [9], [28],

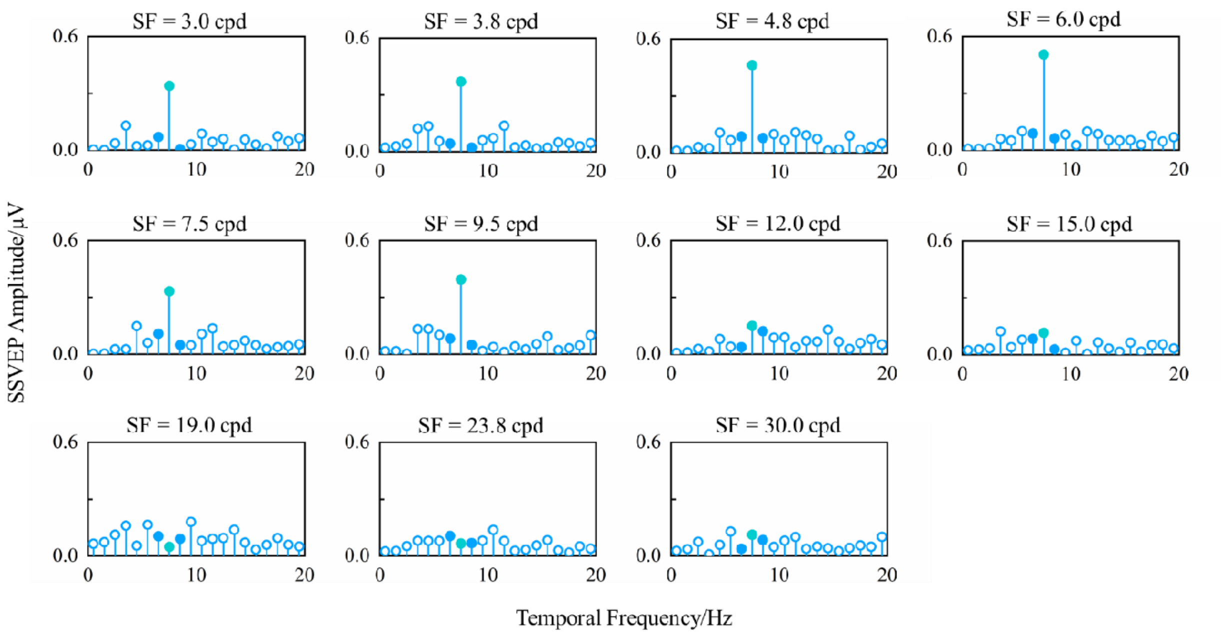

FIGURE 1. DFT analysis of SSVEP response to 11 different spatial frequencies (right eye, subject S3). The solid green point represents the DFT amplitude corresponding to the target frequency of 7.5 Hz. The solid blue point represents the noise value defined by the two adjacent frequencies of 6.5 and 8.5 Hz.

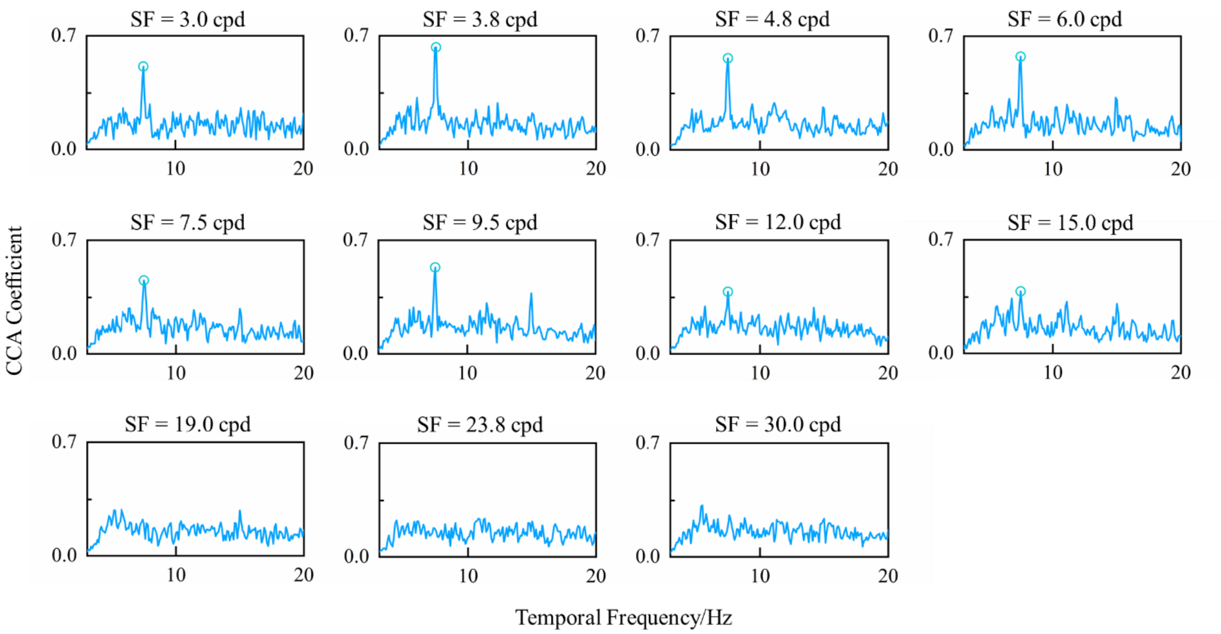

FIGURE 2. CCA analysis of SSVEP response to 11 different spatial frequencies (right eye, subject S3). The hollow green point represents the CCA amplitude corresponding to the target frequency of 7.5 Hz.

we used the "SNR_1" threshold criterion to define the significance of the SSVEP response and the "OR" algorithm in Boolean algebra to reduce the influence of accidental factors, e.g., experimental environment and subjective mental state [15], [28]. The spatial frequency corresponding to the last significant SSVEP response was defined as the SSVEP acuity. Here, the SNR_1 threshold was set as 2.0 [9].

F. STATISTICAL ANALYSIS

All the results of visual acuity testing were converted to a commonly used unit of logMAR for comparison. The one-way repeated-measures analysis of variance (ANOVA), correlation analysis and Bland–Altman analysis, carried out by SPSS (Version 22.0 IBM, Armonk, USA), were used in this study to analyze the difference and agreement between subjective FrACT and objective SSVEP visual

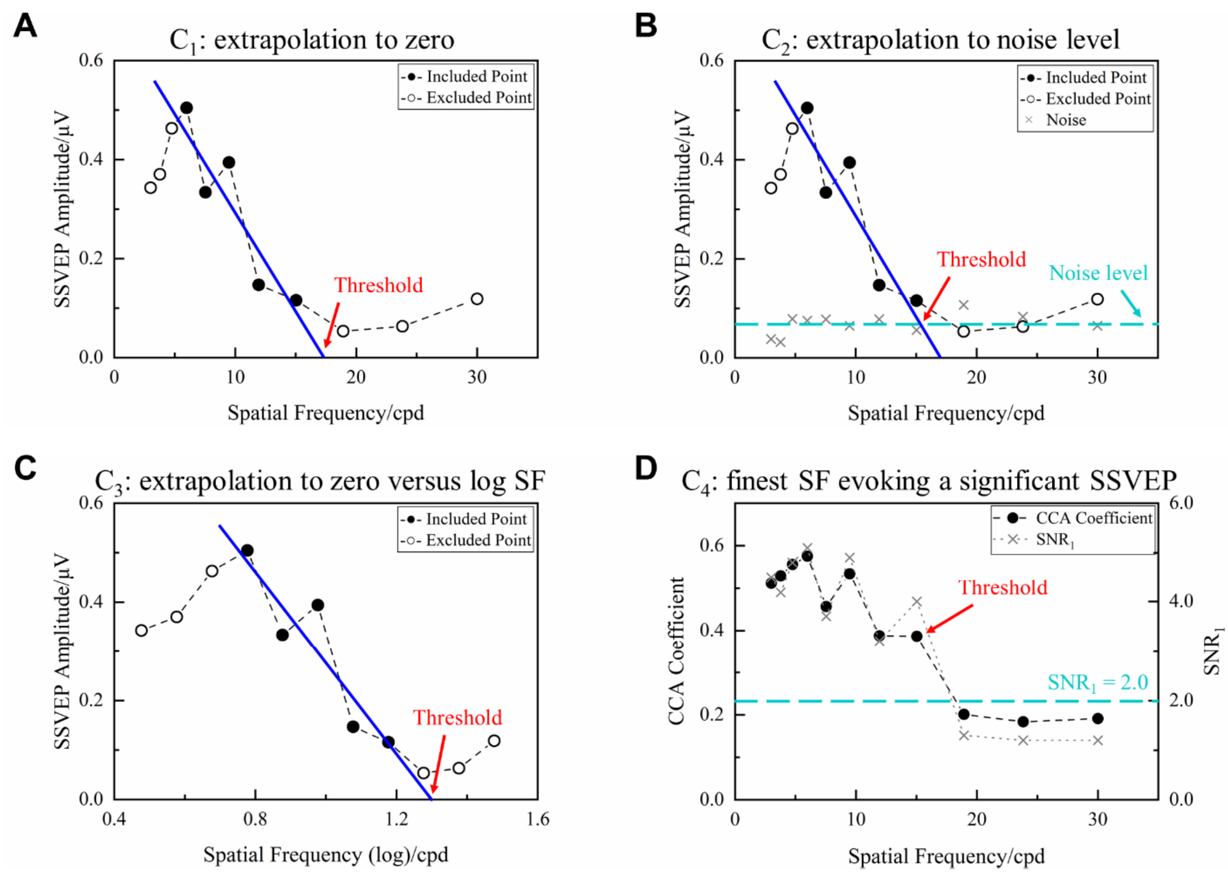

FIGURE 3. Four typical tuning curves corresponding to four threshold estimation criteria (right eye, subject S3). (A) C_1: linear extrapolation to zero. (B) C_2: linear extrapolation to noise level baseline. (C) C_3: linear extrapolation to zero versus log spatial frequency. (D) C_4: finest spatial frequency evoking a significant SSVEP. SF = spatial frequency.

acuity [40]. The *post-hoc* analysis with the Bonferroni correction method for multiple comparisons was also used when necessary.

III. RESULTS

A. SSVEP RESPONSE

Fig. 1 and Fig. 2 show an example of the DFT analysis and CCA analysis of SSVEP response to 11 different spatial frequencies from 3.0 to 30.0 cpd, respectively. There was an evident peak at the target frequency of 7.5 Hz on the DFT spectrum for stimulus paradigms with spatial frequency below 9.5 cpd, and there was an evident peak at the target frequency of 7.5 Hz on the CCA spectrum for stimulus paradigms with spatial frequency below above 15.0 cpd.

B. THRESHOLD ESTIMATION CRITERIA

The typical tuning curves of the four threshold estimation criteria are shown in Fig. 3. As for C_1, there was a regression line between the fourth and eighth points, and the SSVEP visual acuity threshold for C_1 was defined as the spatial frequency of the intercept corresponding to the X-axis. As for C_2, compared to C_1, a noise level baseline was calculated by the mean of eleven noise values of each spatial frequency step, and the SSVEP visual acuity for C_2 was defined as the spatial frequency of the intersection with the noise level baseline. As for C_3, the extrapolation was between the fourth and the eighth point to the 0 μV baseline against the log spatial frequency, and the log spatial frequency of the intercept of the X-axis was then regarded as the SSVEP visual acuity for C_3. As for C_4, the eighth point was corresponding to the finest spatial frequency evoking a significant SSVEP, so the eighth spatial frequency of 15.0 cpd was defined as the SSVEP acuity for C_4. Hence, in Fig. 3, the SSVEP visual acuities for C_1, C_2, C_3 and C_4 were 17.09 cpd, 17.48 cpd, 19.37 cpd (i.e., 1.29 log cpd) and 15.0 cpd, respectively. After the conversion to the unit of logMAR, they were 0.24, 0.29 0.19, and 0.30 logMAR for C_1, C_2, C_3, and C_4, respectively.

C. RELATIONSHIP BETWEEN SSVEP AND FrACT VISUAL ACUITY

The Bland-Altman and correlation analysis were utilized to describe the relationship between the objective SSVEP acuity and subjective FrACT acuity for four threshold estimation criteria, as shown in Fig. 4. The difference between SSVEP and FrACT acuity was all within 0.3 logMAR with most within 0.2 logMAR. The visual acuity estimated by the

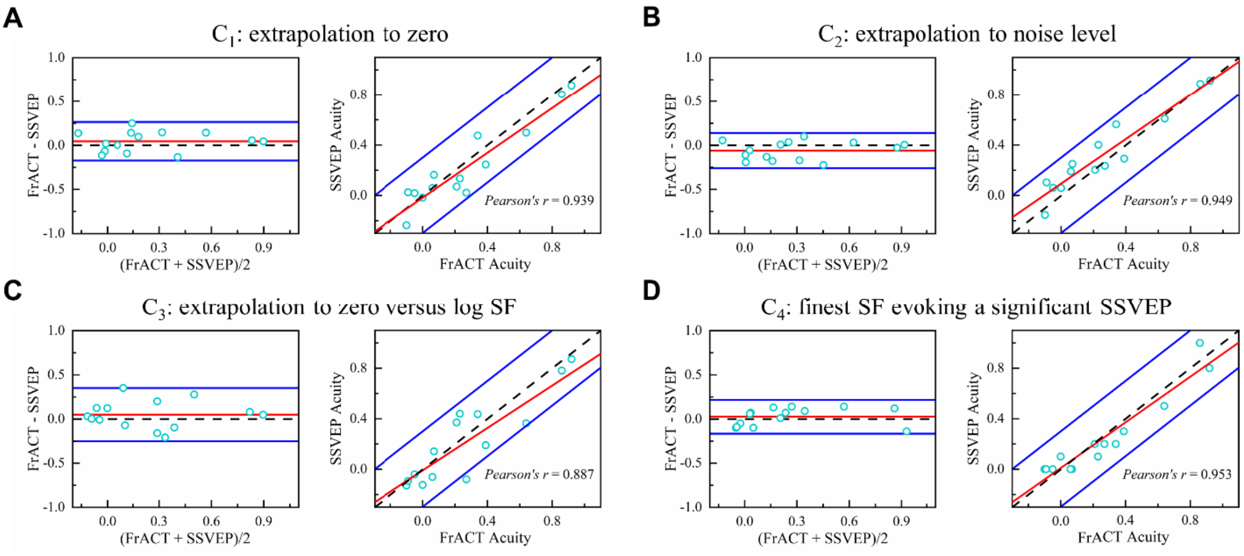

FIGURE 4. Relationship between the subjective FrACT acuity and objective SSVEP acuity for each threshold estimation criterion via Bland–Altman (left of each subfigure) and correlation analysis (right of each subfigure) over all subjects. (A) C_1: linear extrapolation to zero. (B) C_2: linear extrapolation to noise level baseline. (C) C_3: linear extrapolation to zero versus log spatial frequency. (D) C_4: finest spatial frequency evoking a significant SSVEP. For each Bland–Altman analysis subfigure, the red solid line represents the average value of the difference. The blue solid lines represent the 95% limit of agreement. The dashed line represents the reference of the difference of 0. For each correlation analysis subfigure, the red solid line represents the regression relationship between FrACT acuity and SSVEP acuity. The dashed line is the identity line. The blue solid lines represent the deviation of ±0.3 logMAR from the identity line. SF = spatial frequency.

SSVEP of each criterion and FrACT was correlated significantly ($P < 0.001$, respectively), indicating that all these four threshold estimation criteria performed well in SSVEP-based visual acuity assessment. Bland–Altman method found the agreement between the SSVEP and FrACT acuity was all pretty good for the four threshold estimation criteria with all points inside the 95% limit of agreement.

D. COMPARISON BETWEEN SSVEP AND FrACT VISUAL ACUITY

Fig. 5 shows the difference in visual acuity obtained by five various methods, i.e., FrACT and SSVEP of four threshold estimation criteria, over all the subjects. One-way repeated-measures ANOVA revealed that there was a significant difference in visual acuity among these five estimated methods [Greenhouse–Geisser correction: $F_{(2.490,32.376)} = 3.146$, $P = 0.046$]. Subsequently, Bonferroni *post-hoc* analysis was done, as shown in Table 2. Except for visual acuity estimated by C_1 and C_2 with a significant difference ($P < 0.001$), there was no difference in the visual acuity among other methods, demonstrating that these visual acuity estimating methods had a similar performance in evaluating the visual function. The visual acuity estimated by C_1 was slightly higher than that of C_2, as a result of that, some of the magnitude output of a DFT at the stimulus frequency was due to the noise rather than the visually-driven EEG, especially when the spatial frequency was near the threshold [8], [29].

IV. DISCUSSION

The most widely used method for defining the VEP acuity was to extrapolate a straight line regressed through significant

TABLE 2. Bonferroni post-hoc analysis of visual acuity among FrACT and SSVEP of four threshold estimation criteria. ***$P < 0.001$.

Method	C_1	C_2	C_3	C_4
FrACT	$P = 1.000$	$P = 0.494$	$P = 1.000$	$P = 1.000$
C_1	--	$P < 0.001$***	$P = 1.000$	$P = 1.000$
C_2	--	--	$P = 0.071$	$P = 0.513$
C_3	--	--	--	$P = 1.000$
C_4	--	--	--	--

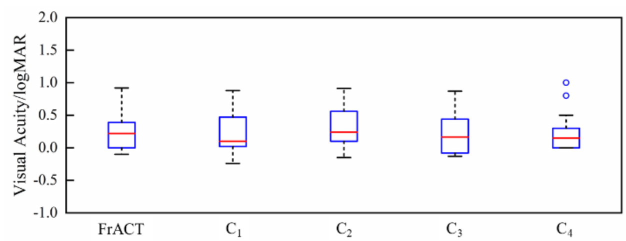

FIGURE 5. Comparison of the visual acuity estimated by FrACT and SSVEP of four threshold estimation criteria over all the subjects.

VEP amplitude plotted against spatial frequency to 0 μV or a noise estimate. Since the VEP response may be also present even below the noise level when the spatial frequency close to the threshold, the commonly used 0 μV as the floor of linear extrapolation was credible [41]. The widely used time-domain averaging of SSVEPs, e.g., Laplacian montage and CAR fusion [15], [42], to reduce noise to negligible levels was perhaps another reason for the use of 0 μV floor, and neuronal noise was low when the point of the absent cortical signal [29]. However, when the spatial frequency close to the threshold, some of the SSVEP response at the stimulus frequency was due to noise rather than the visually-driven EEG, which may result in a slightly better threshold. Therefore, the noise level baseline was used in some studies to avoid this overestimation [22], [43]. Another solution was to extrapolate the noise-corrected magnitude to 0 μV to overcome this small overestimation [15], [35].

Compared with the log spatial frequency scale, a linear spatial frequency scale was justified. VEP amplitude dropped linearly with spatial frequency linearly close to the threshold [21], and the linear extrapolation against linear spatial frequency was insensitive to VEP amplitude changes [44]. If the true relationship between VEP amplitude and linear spatial frequency was linear, the log spatial frequency scaling with linear regression may introduce a systematic error, resulting in an unrealistically better VEP acuity threshold [39], [45]. In this study, 12 of 14 eyes had better SSVEP acuity for log spatial frequency scaling than for linear spatial frequency scaling. Besides, some studies also defined the VEP acuity by curvilinear fitting, e.g., second-order polynomial [18], [46], [47], or modified Ricker [46], between VEP amplitude and spatial frequency, among which a linear spatial frequency scale has been commonly used [8].

As for the threshold definition of the finest spatial frequency evoking a significant SSVEP, in general, it showed an underestimate compared to the threshold obtained by extrapolation [21], [48], since the extrapolation technique had a short extrapolation process between the last significant SSVEP amplitude and the interception of the baseline. However, in this study, the difference between the finest technique and all the three extrapolation methods was nonsignificant, maybe as a result of the two EEG signal processing methods, showing that our finest spatial frequency technique, i.e., significance determination by CCA combined with "OR" operation, had an equally good performance as extrapolation technique in SSVEP visual acuity assessment. Moreover, the precision of the estimated SSVEP acuity by the finest spatial frequency technique depended strongly on the spatial frequency sampling density when close to the threshold. Hence, compared to the extrapolation technique, the finest spatial frequency technique had the potential to find the acuity threshold faster by concentrating on the VEP response close to the threshold, since it did not require a sufficient spatial frequency range to characterize an extrapolation function between the VEP magnitude and spatial frequency [10]. Besides, the finest spatial frequency technique can also be used as an additional and integrated strategy when the extrapolation technique failed to determine a VEP threshold due to the notches or low amplitudes at the intermediate spatial frequencies [12], [15], [17], [49].

V. CONCLUSION

In this study, we compared the extrapolation technique and the finest spatial frequency technique in SSVEP visual acuity estimation for the first time. We estimated SSVEP visual acuity by using the commonly used three linear extrapolation approaches, i.e., linear extrapolation to zero, linear extrapolation to noise level baseline and linear extrapolation to zero versus log spatial frequency, and an improved finest spatial frequency technique, i.e., significance determination by CCA combined with "OR" operation, and then compared them with subjective FrACT visual acuity, respectively. The correlation and agreement between subjective FrACT acuity and objective SSVEP acuity were all pretty good, demonstrating that all of these four threshold estimation criteria had a good performance in SSVEP visual acuity assessment.

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