Person Verification Using Electroencephalograms Evoked by New Imperceptible Vibration Stimulation

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***Abstract*—This paper examines how to identify individuals using their electroencephalograms (EEGs) evoked by imperceptible vibration stimulation. Based on the knowledge of evoked EEGs by tactile stimulation, we learned that evoked responses could occur within a shorter time. In this paper, we propose measuring evoked EEGs for 100 ms. We confirm the presence of an event-related response in the measured EEGs and evaluate the individuality and verification performance of the measured EEGs as biometrics. The results demonstrate that the proposed stimulus presentation method is superior to the conventional method.**

***Index Terms*—biometrics, electroencephalogram, imperceptible vibration stimulation, event-related response, t-test**

I. Introduction

In recent years, biometrics has been increasingly used in daily life; for example, in the use of fingerprints and face images to log on to smartphones. However, such biometric data always involve body surfaces; therefore, they can be easily stolen (captured) using digital devices, such as cameras. If the data are stolen, copies can be made. In addition, fingerprint and face recognition assume one-time-only authentication, which causes the risk of spoofing. After authenticating a regular user of a system using his/her biometrics, even if the user is replaced by an imposter who does not have license to use the system, it is impossible to detect the spoofing using biometrics based on one-time-only authentication.

To address this problem, continuous authentication has been proposed, as it is more effective than one-time-only authentication. As biometrics that are suitable for continuous authentication, brainwaves or electroencephalograms (EEGs) have attracted attention [1]. The signals are always produced as long as the person is alive, so this information can be continuously measured. In addition, as anyone can utilize brain waves, they are the most accessible biometric data. Since brain waves are detectable only when the person is wearing a brain wave sensor, it is also not possible for others to covertly steal the data.

However, conventional studies have made no mention of the applications using brainwaves as biometrics. To use brainwaves requires users to wear a brain-wave sensor, but this takes time since users set many electrodes on their scalp while moving their hair. It is not imaginable to do that when, for example, users enter a room, log in a PC, or use an ATM. Therefore, brain waves as biometrics is not suitable for one-time-only authentication. On the other hand, once users wear a brain-wave sensor, it is comparatively rare for them to be conscious of wearing it since they are concentrating on using a system.

However, to wear the brain-wave sensor is indeed a weak point for brain waves as biometrics. Therefore, operator verification of a high-security system is suitable for authentication using brain waves. Operators are required to wear a brain-wave sensor and they are continuously verified while using the system. For instance, in a remote-education system, students who are trying to obtain an academic degree or public qualification should be authenticated while learning. Operators of public-transportation systems should be authenticated while operating the systems since hundreds of human lives depend on them. There are other examples: aircraft pilots, emergency-vehicle drivers, and military-weapon operators.

From that viewpoint, we have studied person authentication using brainwaves [2], [3]. In particular, EEGs elicited by a personalized stimulus are more effective than spontaneous EEGs. However, the stimulus must be imperceptible to humans. If a perceptible stimulus is presented to users while they use a system, their usage of the system will be disturbed. Therefore, we have used impercitible stimulation for eliciting EEGs. In Refs. [4] and [5], an image inserted in a video with a fast frame rate (8 ms) and ultrasounds extracted from high-resolution sounds were used as impercitible stimulation, respectedly. We also proposed the use of imperceptible vibration stimulation [6]. EEGs for 30 s were measured after stimulation, their inducibility and individuality were examined, and their verification performance was evaluated. However, such a long measurement time is not suitable for person verification. From the knowledge of evoked EEGs by tactile stimulation, we determined that evoked responses could occur in EEGs within a shorter time. In this paper, we propose measuring evoked EEGs for 100 ms, and examine the presence of an event-related response (ERP) in the measured EEGs. ERP is the measured brain response that is caused by a specific sensory, cognitive, or motor event. In addition, we examine the individuality of the measured EEGs using the *t*-test, and evaluate the verification performance of the measured EEGs.

Fig. 1. Dedicated measuring device with an vibration actuator.

II. Person verification using electroencephalogram evoked by imperceptible vibration stimulation

Tactile sensations are cutaneous (skin) sensations, such as touch, pressure, pain, and temperature. These sensations are perceived by the cutaneous receptor in the skin and sent to the brain as signals, which ultimately allow the brain to experience perception. Tactile simulation is a collective term for pressure stimulation, temperature stimulation, vibration stimulation, and electrical stimulation.

In Ref. [6], vibration stimulation was applied to the palms of the experimental participants using a vibration actuator. Figure 1 shows the dedicated measuring device with the actuator. Imperceptible vibration stimuli whose frequencies were slightly higher than the participants' individual sensation thresholds were used as imperceptible stimuli. The participants' sensation thresholds were determined prior to EEG measurement. There were 20 participants in the experiment, and each sat in a chair and relaxed with his/her eyes closed and ears plugged. Each measurement was 30 s. After the preprocessing of noise in the measured EEGs, power spectra were calculated using a fast Fourier transform (FFT). The power spectral elements were accumulated in θ (4–8 Hz), α (8–13 Hz), β (13–26 Hz), and γ (26–43 Hz) wavebands, and the ratio to the total spectral power in all bands (4–43 Hz) was calculated in each band and called the content ratio. The ratios in four bands were used as an individual feature with four dimensions. Euclidian distance matching was used as the verification method, and the verification performance was evaluated using the equal error rate (EER). A false acceptance rate (FAR) is the rate of accepting imposters, and a false rejection rate (FRR) is the rate of rejecting genuine users, and there is trade-off between these error rates. The EER is the rate where the FAR equals to the FRR. A smaller EER shows a better performance. Five cross-validations for eliminating the effects of choosing data for creating a template and data for testing were performed, and the average EER from fourteen electrodes was 33.7%. Additional details are provided in [6].

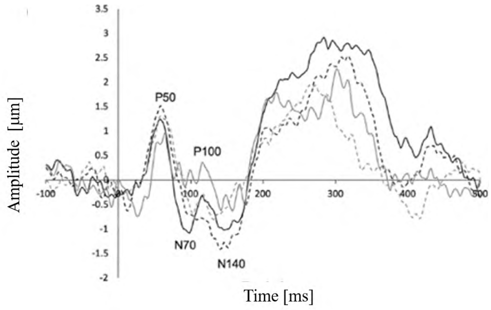

Fig. 2. Example of event related responses (ERP) [8].

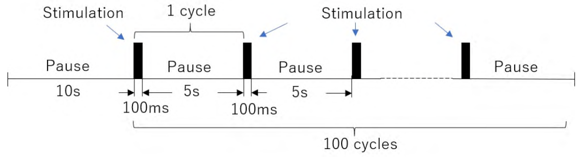

Fig. 3. New stimulus presentation.

III. New stimulus presentation

Measurements that are 30 s long are not suitable for person authentication; therefore, shorter measurement times are required.

A. Findings of evoked electroencephalograms by tactile stimulation

After surveying studies on evoked EEGs by tactile stimulation, we discovered that evoked responses could occur in EEGs within a shorter time after stimulus presentation [7]–[12]. In particular, ERPs from P50 to N70 or P100 to N140 occur approximately 50 ms or 100 ms after stimulation, respectively, where P and N represent a positive and negative potential, respectively. An example is provided in Fig. 2. We also found that when stimulation is presented for a long time, humans become accustomed to it.

B. Imperceptible tactile stimulation

The findings discussed in Sect. III-A pertain to perceptible tactile stimulation. However, there are no findings on EEG responses to imperceptible tactile stimulation in humans. It is thus not guaranteed that the ERPs in Fig. 2 also occur for imperceptible stimulation.

We therefore constructed a new stimulus presentation environment in which imperceptible vibration was repeatedly presented in intervals to each experimental participant, as illustrated in Fig. 3. One cycle consisted of stimulus presentation for 100 ms and an interval of 5 s and was repeated 100 times. There were five experimental participants, who sat in a chair and relaxed with their eyes closed and ears plugged. The brain wave sensor used was EPOC+ produced by EMOTIVE in San Francisco, U.S.A., whose sampling frequency was 256 Hz and measurable frequency range was 0.2–43 Hz. It had 14 electrodes based on the extended international 10–20 system.

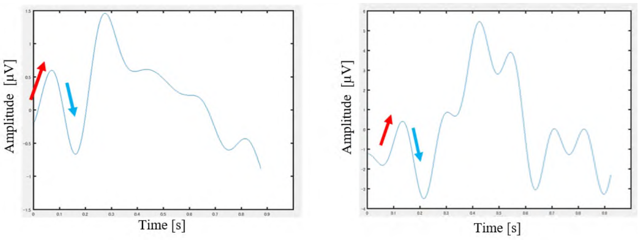

Fig. 4. Ensemble-averaged electroencephalograms.

The measured EEG tended to have a trend and/or ground bias. From each EEG, the trend and bias were eliminated using an approximate straight line obtained using the least-squares method. In addition, each EEG was processed using a filter with a 4–43-Hz bandpass. In each EEG, if each amplitude exceeded three times the standard deviation of all amplitudes, it was replaced by 0. This was intended to eliminate spike noise.

After these preprocessing steps, EEG data for 1 s from the start of each stimulus were extracted 100 times, and the 100 EEGs were ensemble averaged. In general, an ERP is very weak; therefore, it can be extracted by ensemble averaging many synchronized EEGs.

Figure 4 presents examples measured at the F3 electrode. In this measurement, synchronization was achieved as follows. Software for oscillating the vibration actuator and for EPOC+ was installed on the same computer, and each had a window of operating time. EEG measurement was always started before initiating the vibration. After starting the measurement, a vibration was given to an experimental participant. During the measurement, both windows on the computer's display were captured by a digital camera, and from the captured image, the oscillating time of vibration and the measured time of the EEG were obtained. The time delay was obtained by subtracting the oscillating time from the measuring time, and the sampled data corresponding to the delay were deleted from the measured EEG data. As a result, strict synchronization was not achieved, and it was thus impossible to examine the accurate delay time from the start of the stimulation. However, the response from a positive potential to a negative potential was confirmed, as illustrated in Fig. 4. As far as we know, it was confirmed for the first time that evoked EEG is generated even by imperceptible vibration stimulation. Verification using EEGs including these ERPs may also lead to improved performance.

IV. Evaluation of Evoked Electroencephalograms by New Stimulus Presentation

To evaluate the effect of the proposed stimulus presentation method, we measured EEGs using the proposed method, evaluated their individuality, and evaluated their verification performance.

A. Individual vibration frequency

Prior to EEG measurement, the imperceptible vibration frequency for each experimental participant was determined. There were 10 participants in the experiment, and all were male. They sat in a chair and relaxed with their eyes closed and ears plugged.

First, their sensation thresholds were investigated. While increasing the vibration frequency by 10 Hz, the participants were instructed to respond when they sensed the vibration. The number of measurements per participant was 15.

Next, a 95% confidence interval among the sensed frequencies of each participant was calculated. 50 Hz was added to the upper limit of the 95% confidence interval, which resulted in a personalized vibration frequency for each participant. Table I presents the personalized vibration frequencies of all participants.

TABLE I
PERSONALIZED VIBRATION FREQUENCIES (HZ).

Sub.	A	B	C	D	E	F	G	H	I	J
Fre.	630	810	650	550	700	850	690	740	630	810

B. Measurement of electroencephalograms

Using the obtained personalized vibration frequencies, we measured the EEGs of participants when presenting them with imperceptible tactile stimulation. The presentation cycle of the stimuli was the same as that described in Sect. III-B. However, the number of presentation cycles was 10, which corresponds to approximately 50 s. Measurements were performed ten times for each participant. To avoid the influence of successive measurements on evaluation, the interval between them was more than six hours. In addition, assuming the spoofing attack, the participants were given vibrations whose frequencies were personalized for other individuals. In total, each participant had 10 EEGs as genuine data and 9 EEGs as imposter data.

C. Evaluation of individuality

For person authentication, it is important for EEGs evoked by imperceptible stimulation to have individuality. However, it is not simple to extract the individuality from ERPs that can be only extracted by ensemble averaging of many synchronized EEGs. In actual application, multiple measurements are acceptable in the enrollment phase for creating a template. However, the measurement of many EEGs in the verification phase cannot be performed because it is inconvenient for users. Therefore, we used the content ratio that can be extracted from an EEG spectrum as an individual feature, as in [6]. Furthermore, to confirm individuality, we performed Welch's t-test using the content ratio of a participant and those of other participants. Welch's t-test is generally used when two compared groups have different variances, and it is defined as

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}, \qquad (1)$$

where x represents the sampled data of each group, n represents the quantity of data, $\overline{x}$ represents their mean, and s^2 is their unbiased variance. A p value is calculated using the

TABLE II
t VALUES AT ALL ELECTRODES FOR EACH PARTICIPANT IN EACH WAVEBAND.

θ	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	0.036	0.013	0.182	0.208	0.010	0.268	0.534	0.000	0.000	0.001	0.154	0.007	0.020	0.027
B	0.992	0.093	0.530	0.979	0.007	0.290	0.287	0.869	0.533	0.619	0.632	0.299	0.755	0.342
C	0.314	0.115	0.486	0.581	0.963	0.590	0.000	0.001	0.492	0.351	0.998	0.365	0.176	0.728
D	0.842	0.023	0.640	0.605	0.001	0.023	0.766	0.061	0.435	0.650	0.197	0.796	0.270	0.000
E	0.485	0.003	0.076	0.229	0.643	0.001	0.000	0.000	0.592	0.699	0.794	0.113	0.672	0.373
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G	0.012	0.070	0.000	0.000	0.338	0.005	0.003	0.006	0.392	0.554	0.056	0.534	0.331	0.250
H	0.004	0.620	0.063	0.736	0.026	0.006	0.000	0.040	0.694	0.006	0.973	0.347	0.758	0.631
I	0.578	0.207	0.300	0.394	0.027	0.070	0.329	0.052	0.028	0.477	0.840	0.377	0.937	0.829
J	0.000	0.000	0.019	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.166	0.003	0.000

α	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	0.804	0.174	0.166	0.498	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.938	0.018	0.592
B	0.000	0.000	0.010	0.000	0.151	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D	0.003	0.686	0.004	0.045	0.077	0.000	0.064	0.206	0.000	0.051	0.716	0.012	0.382	0.432
E	0.556	0.019	0.038	0.655	0.001	0.307	0.000	0.054	0.000	0.039	0.474	0.020	0.483	0.240
F	0.837	0.023	0.428	0.007	0.624	0.000	0.679	0.466	0.424	0.003	0.006	0.140	0.017	0.669
G	0.000	0.000	0.000	0.000	0.995	0.000	0.000	0.000	0.004	0.895	0.000	0.000	0.001	0.000
H	0.000	0.000	0.000	0.000	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
I	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.171	0.005	0.000	0.000	0.000	0.000	0.001
J	0.605	0.611	0.490	0.000	0.195	0.044	0.716	0.000	0.179	0.000	0.000	0.981	0.219	0.603

β	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	0.285	0.845	0.044	0.768	0.000	0.000	0.000	0.017	0.002	0.238	0.223	0.044	0.369	0.047
B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	0.000	0.001	0.000	0.000	0.667	0.110	0.014	0.001	0.000	0.081	0.001	0.001	0.007	0.001
D	0.000	0.059	0.000	0.014	0.009	0.000	0.635	0.097	0.000	0.070	0.040	0.002	0.043	0.000
E	0.039	0.000	0.555	0.007	0.000	0.073	0.004	0.143	0.000	0.000	0.066	0.894	0.040	0.158
F	0.001	0.000	0.000	0.000	0.361	0.544	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.000	0.000	0.000	0.000
H	0.000	0.000	0.000	0.000	0.198	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
I	0.000	0.006	0.000	0.011	0.660	0.002	0.154	0.028	0.078	0.001	0.000	0.004	0.000	0.002
J	0.000	0.000	0.000	0.000	0.083	0.112	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000

γ	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4
A	0.046	0.725	0.002	0.608	0.002	0.000	0.000	0.000	0.000	0.000	0.011	0.138	0.110	0.035
B	0.000	0.000	0.019	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
C	0.000	0.000	0.000	0.000	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D	0.001	0.026	0.009	0.012	0.001	0.000	0.001	0.001	0.000	0.089	0.789	0.040	0.270	0.001
E	0.197	0.000	0.002	0.077	0.288	0.631	0.298	0.165	0.013	0.413	0.013	0.001	0.290	0.007
F	0.000	0.000	0.000	0.000	0.000	0.076	0.000	0.490	0.014	0.000	0.000	0.000	0.000	0.001
G	0.000	0.000	0.000	0.007	0.059	0.011	0.919	0.361	0.542	0.209	0.692	0.000	0.024	0.000
H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
I	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.065	0.000	0.000	0.000	0.000	0.000	0.000
J	0.049	0.328	0.227	0.000	0.001	0.119	0.481	0.000	0.001	0.000	0.000	0.008	0.740	0.018

t value. In general, when the p value is less than 0.05, it is assumed that there is a difference between the two compared groups.

For statistical analysis, it is important to use sufficient data. To increase the quantity of data, each EEG obtained in 10 cycles was divided into 10 (5-s-long) data, which resulted in 10 $\times$10 data from each participant and 9 $\times$10 data from other participants.

p values at all electrodes for each participant in each waveband are summarized in Table II. Colored cells indicate that the p value is less than 0.05. In these results, the number of colored cells is relatively large, in particular in α, β, and γ wavebands. This suggests that there is a difference between the evoked EEG of an individual and those of other individuals. This is important evidence that demonstrates that the proposed stimulation method causes different responses in EEGs among different individuals.

D. Evaluation of verification performance

To evaluate the effectiveness of the proposed stimulation method, we compared its verification performance with that of the stimulation method used in [6]. However, in [6], an EEG of 30 s was used for extracting individual features, whereas in the proposed method, an EEG of 5.1 s was used in each cycle. To prepare EEG data in the same condition, we created an EEG of 30 s by connecting an EEG for 3 s after stimulus presentation in each cycle 10 times.

From the 30-s-long EEG, the content ratios in all wavebands were calculated and used as individual features. Euclidian distance matching was used as the verification method. From 10 EEGs of genuine data, five EEGs were used to create a template, while the remaining five were used for verification. There were five cross-validations, and the combination of five for the template and five for verification was randomly determined in each validation. Evaluation was performed using EERs.

EERs at all electrodes and their averages are compared with those reported in [6] in Table III. In this table, each EER is the mean of five EEGs obtained by cross validation. All EERs were reduced by approximately 10% compared with those in [6]. In particular, they were reduced by 18.3% at the P7 electrode. Therefore, we conclude that the proposed stimulation method is effective for person verification using evoked EEGs by imperceptible tactile stimulation.

For reference, Table IV displays the EERs when using EEG data for 1 s (one cycle) after stimulus presentation. Almost all EERs were higher than those using 30-s-long data. The reason is that the quantity of sampled data for the FFT analysis was greatly reduced when using 1 s EEG data. The quantity of sampled data for FFT analysis directly affects frequency resolution; as the number of sampled data decreases, the frequency resolution also decreases. Because the sampling rate of EPOC+ was 256 Hz, the quantity of sampled data for 1 s was 256, while the quantity of sampled data for 30 s was

TABLE III
COMPARISON OF EERS AT ALL ELECTRODES AND THE MEANS.

	AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	Ave.
Ref. [6]	32.5	31.1	34.0	33.0	36.9	34.6	37.6	35.0	31.9	33.8	34.0	33.8	32.2	31.5	33.7
Proposed	20.4	20.5	24.6	22.7	35.3	16.3	23.8	26.6	24.6	21.0	25.9	27.2	21.6	25.2	24.0

TABLE IV
EERS USING 1 S DATA AT ALL ELECTRODES AND THE MEAN.

AF3	F7	F3	FC5	T7	P7	O1	O2	P8	T8	FC6	F4	F8	AF4	Ave.
36.8	30.4	40.1	36.7	40.1	38.2	32.4	40.8	43.6	36.1	33.2	38.0	32.8	38.7	37.0

7,680. The frequency resolution when using 1 s data was 1/30 of that using 30 s data. This reduction in frequency resolution led to degradation of the verification performance.

From the standpoint of practical use, it is necessary to shorten the measurement time as much as possible, as a long measurement time causes a response delay in authentication. However, as observed in Figs. 2 and 4, evoked responses continue for almost 1 s after stimulus presentation. In vibration stimulation studies using cyclic stimulus presentation, various researchers have used an interval of 2–6 s [13]–[17]. An interval between stimuli is necessary for accurately extracting an ERP. The proposed cyclic stimulus presentation is effective for improving the frequency resolution in FFT analysis while increasing the EEG measurement time.

V. CONCLUSIONS

We aim to realize person verification using EEGs evoked by imperceptible vibration stimulation. In this paper, we measured evoked EEGs for 100 ms, confirmed ERPs in the measured EEGs, examined the individuality of the measured EEGs, and evaluated the verification performance of the measured EEGs. The results confirmed that the proposed stimulus presentation method displayed superior performance to the conventional method. However, the reduced EEG measurement time in the proposed method caused the deterioration of the frequency resolution, which should be addressed in future work.

To increase the reliability of the results obtained in this study, it is necessary to increase the number of experimental participants. Future work also includes introducing additional individual features that are effective for enhancing differences between individuals. In addition, future research should involve developing learning-based verification methods with strong verification performance. To introduce a total decision method, in which the verification results in all or part of electrodes are fused is a simple approach for improving the verification performance.

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