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Somatosensory Evoked Potentials Elicited by Stimulating Two Fingers from One Hand - Usable for BCI?

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***Abstract*— Steady-state somatosensory evoked potentials (SSSEPs) have been elicited using vibro-tactile stimulation on two fingers of the right hand. Fourteen healthy subjects participated in this study. A screening session, stimulating each participant's thumb, was conducted to determine individual optimal resonance-like frequencies. After this screening session, two stimulation frequencies per subject were selected. Stimulation was then applied simultaneously on the participant's thumbs and middle finger. It was investigated whether it is possible to classify SSSEP changes based on an attention modulation task to determine possible BCI applications. A cue indicated the participants to shift their attention to either the thumb or the middle finger. Offline classification with a lock-in analyzer system (LAS) and a linear discriminant analysis (LDA) classifier was performed. One bipolar channel and no further optimization methods were used. All participants except one reached classification results above chance level classifying a reference period without focused attention against focused attention either to the thumb or the middle finger. Only two subjects reached accuracies above chance, classifying focused attention to the thumb vs. attention to the middle finger.**

I. Introduction

Different strategies are used nowadays for Brain-Computer Interfaces (BCIs). Prominent examples are BCIs controlled via sensorimotor rhythms [1] or evoked potentials (EPs) [2]. Visual evoked potentials (VEPs) can occur after row and column flashes from a P300 speller [3]. In [3], the occurrence and usability of, for example, the P300 component [4] was analyzed. EPs can also be utilized for BCI control using amplitude modulation of steady-state EPs (SSEPs) through shifting attention [5], [6]. A major drawback of VEP-based BCI systems is the requirement of a functional visual system. Patients suffering from a locked-in syndrome or amyotrophic lateral sclerosis (ALS) can lose control over their eyes and the ability to lift their eyelids [7], but their somatosensory system seems to remain functional. As an alternative, SSEPs could also be elicited using tactile stimulation, producing steady-state somatosensory evoked potentials (SSSEPs) [8]. These potentials have already been successfully applied for BCI control, stimulating the index fingers of both hands [9]. Control was gained by shifting attention to a target finger. Person dependent stimulation frequencies were obtained via a simple screening process. Classificaion accuracies of up to 80 % could be reached by classifying focused attention on the left or the right index finger during tactile stimulation. Applying vibratory stimulation also produces cortical activity beyond the primary somatosensory system, especially when focusing on a target stimulus [10]–[12]. Therefore channels not just covering the primary somatosensory cortex could lead to an increased BCI performance.

The goal of this work was to investigate whether users could gain control through a BCI based on attention modulation by just stimulating fingers of one hand using a person specific stimulation frequency selection. If it is possible to distinguish attention modulation within one hand, it could become feasible to build a BCI with more than two classes by stimulating multiple fingers on both hands.

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II. Methods

A. Measurment Setup and Participants

Tactile stimulation was applied to the finger tips of the thumb and the middle finger of the right hand using C2 tactors [Engineering Acoustics, Inc., Casselberry, FL, USA]. The stimulation signal was produced via a custom-built signal generator generating a 200 Hz sine, modulated with a rectangular signal for stimulation as suggested by Müller-Putz et al. [9]. The resulting stimulation signals were short 200 Hz pulses with a given frequency. The measurement was divided into the parts: (i) screening and (ii) focused attention. Electrode coordinates were gathered using ELPOS from zebris [zebris Medical GmbH, Isny, Germany]. Fourteen paid subjects participated in the studies (50 % male, 50 % female, mean age: 25.64 ± 2.6 years).

B. EEG Recording

Forty-eight Ag/AgCl electrodes were used for EEG recording with linked references as shown in Fig 1. Three g.USBamps [Guger Technologies OG, Graz, Austria] were used for EEG recording with a sampling rate of 2.4 kHz. Impedances were kept below 5 kΩ. All EEG measurements were done in a shielded room.

C. Measurement Procedure

1) Screening: According to [13], every person reacts in a different way to tactile stimulation with an individual resonance-like frequency. To determine person specific tuning curves, a screening measurement was conducted by stimulating the participant's thumb with stimulation frequencies

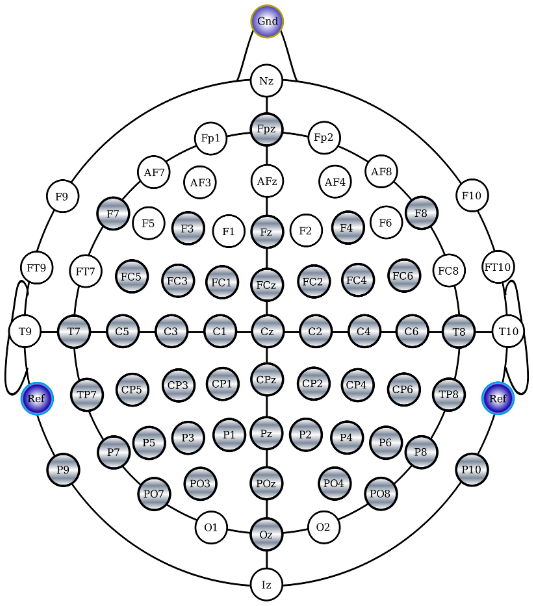
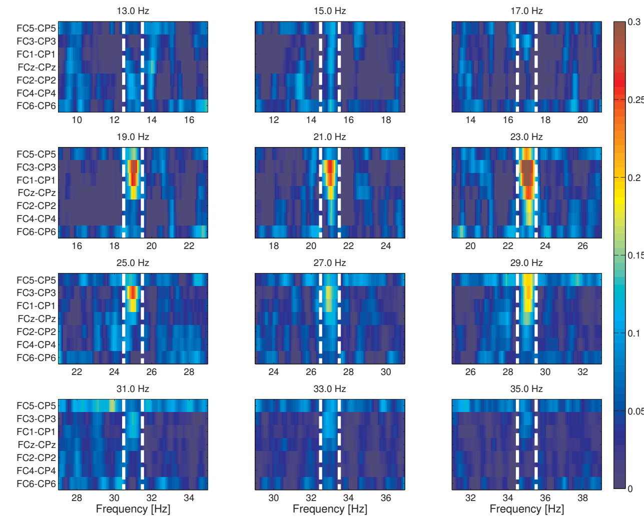
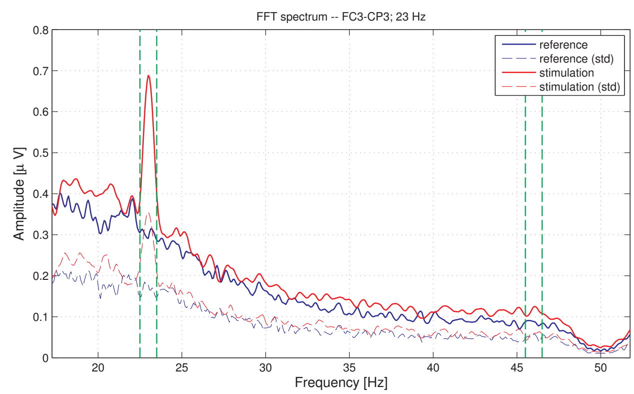


Fig. 1. International 10–20 system electrode setup used for measurement. Recorded electrode positions are highlighted in gray, reference electrodes were placed at left and right mastoids, and a ground electrode was mounted on the participant's nose.



(a) FFT difference maps used to determine stimulation frequencies with the highest SSSEP response. Every plot belongs to the time window of one stimulation frequency, the x-axis shows the frequency, and the y-axis shows seven bipolar channels over the primary sensory and motor regions. Blue colored regions indicate a low amplitude, while red and yellow colored sections show an increased amplitude. Applied stimulation frequencies are highlighted with white dashed lines.



(b) FFT spectrum of bipolar channel FC3–CP3 during stimulation with 23 Hz used for manual inspection. The red lines represent the mean frequency response and its standard deviation during stimulation, and blue lines during reference period. The range of the stimulation frequency and its 2^{nd} harmonic are highlighted with green dashed lines.

Fig. 2. FFT maps and FFT spectra used to determine optimal stimulation frequencies for further measurements from participant s1.

from 13 Hz to 35 Hz, in 2 Hz steps. Only the thumb was stimulated as the tuning curve is assumed to be similar on all fingers [14]. Every frequency was stimulated randomly 60 times for 2 s. Reference periods without tactile stimulation were placed in the screening paradigm. The screening was divided into 6 runs, every run lasting about 8 min. Participants were distracted to avoid concentrating on the stimulated finger. They had to perform a mathematical task during the screening: add or subtract randomly appearing numbers on a screen. After the screening, FFT difference maps (fast fourier transform) were calculated based on the screening data to show power changes during stimulation. An example is presented in Fig. 2(a). This maps outline the difference between the FFT spectra during reference and during stimulation. FFT spectra from the bipolar channel FC3-CP3 from time-intervals during stimulation were plotted as shown in Fig. 2(b). Two frequencies with the highest amplitudes during stimulation were selected as stimulation frequencies for the following paradigm.

2) Focused Attention: This paradigm was divided into single trials. Every trial consisted of a 3 – 3,5 s reference followed by a 4 – 4,5 s focused attention period. During the reference period, participants were instructed to merely look at the blank screen. Tactile stimulation was applied during both periods with the frequencies selected from the screening. Randomly appearing amplitude changes, called "twitch" [9], were mixed into the stimulation to facilitate focusing on a finger by counting the twitches. A fading text indicated the respective target finger. Every class (target finger to focus on) was repeated 80 times.

D. Analysis

All data were visually inspected before analysis. EOG (electrooculogram) and EMG (electromyogram) artifacts were manually marked; trials containing EMG artifacts were discarded from further calculations.

1) Band Power Tuning Curves: Tuning curves, based on relative band power (BP) increase [13], were calculated for comparison with the FFT maps. To obtain relative BP values, the BP during stimulation with a single frequency was related to the respective reference interval. For all relative BP values, 95 % confidence intervals using a bootstrap algorithm [15] provided by Matlab [The MathWorks Inc., Natick, USA] were computed with 1000 bootstrap samples and the mean as the bootstrapping function.

2) Classification: The amplitude output of a lock-in analyzer system (LAS) [9] and an LDA (linear discriminant analysis) classifier (Fishers LDA) were utilized for classification. As a first attempt, the bipolar channel FC3–CP3, which showed the highest amplitudes in the stimulation frequency range inside the FFT maps, was used for classification. This channel selection was also used to obtain comparable results with [9]. The LAS output was smoothed using a moving average filter (length 1 s) before classification. A classifier was trained using 10 x 10 cross validation. The classes attention on thumb or middle finger were classified against the reference period and against each other.

III. Results

All figures presented were obtained from participant s1, who was randomly selected.

A. Band Power Tuning Curves

Fig. 3 shows relative BP values for different bipolar channels of one participant. An emergence of a tuning curve is visible at bipolar channels over the left hemisphere. Channels covering the right hemisphere show merely a slight or no increase. A maximum relative BP increase can be seen at FC3–CP3 around 23 and 25 Hz.

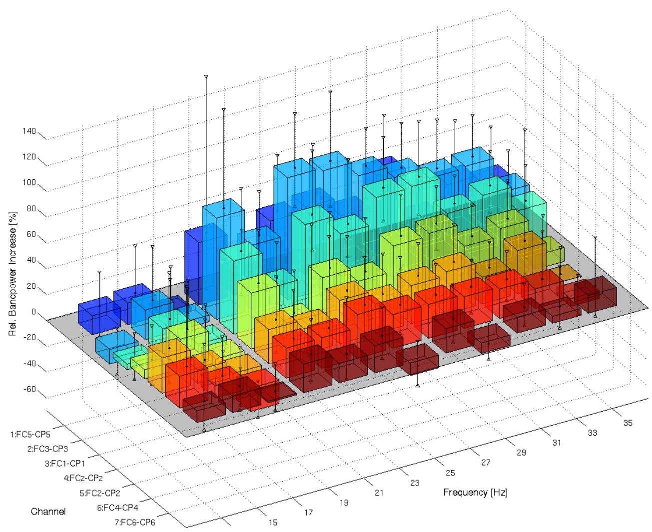


Fig. 3. Relative BP increase tuning curves during stimulation for seven bipolar channels over the primary sensory and motor cortex for participant s1. The respective stimulation frequency is shown on the x-axis, channels are displayed on the y-axis and the relative BP increase is shown on the z-axis. Every channel is plotted using the same color. Vertical lines show the 95 % confidence interval (computed using bootstrapping [15]).

B. Classification

Classification results for participant s1 can be seen in Fig. 4. The results shown in this figure were 10x10 cross validated with 79 trials per class. Maximum accuracies of 74 % and 73 % for the respective classes vs. reference and 56.7 % for thumb vs. middle finger were reached by this participant. In both cases, classifying against reference, the classification accuracy was above chance level [16]. Tab. I shows the classification accuracies, their resonance-like frequency and the selected frequencies for stimulation for all participants. Thirteen of them reached accuracies above chance for at least one class against reference. However, only two participants reached a classification accuracy slightly above chance, classifying attention on the thumb vs. attention on the middle finger. The mean accuracy for all participants was 66.8 % (± 5,7) for thumb vs. reference, 66.6 % (± 5.1) for middle finger vs. reference and 58.6 % (± 2.0) for thumb vs. middle finger.

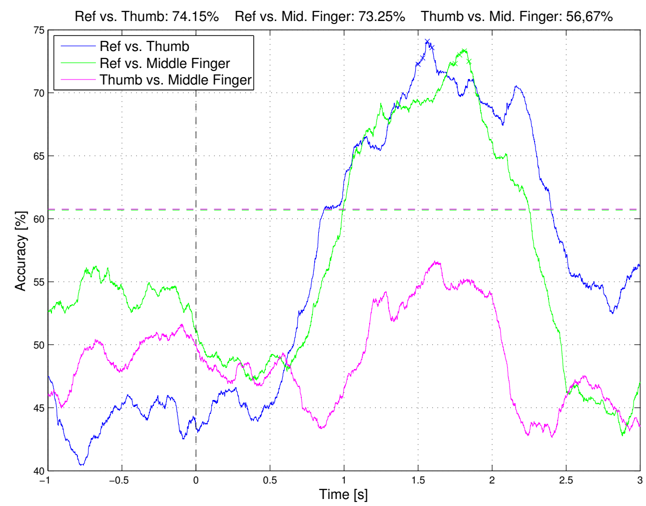


Fig. 4. Classification accuracies for attention on thumb or middle finger against the reference period and thumb vs. middle finger for participant s1. The blue line represents switching attention to the thumb classified against reference and the green line the attention to the middle finger against reference. The magenta colored line shows the classification accuracy of thumb vs. middle finger. The horizontal dashed line indicates the chance level at 61 % for a significance level of 5 % with 79 trials per class [16]. A vertical dashed line indicates the trial start, when the participants started shifting their attention to a single finger.

IV. Discussion

This study assessed the possibility of successfully classifying steady-state somatosensory evoked potentials on two fingers from the same hand using attention modulation. FFT calculations and relative BP tuning curves were utilized to determine optimal stimulation frequencies.

A. Band Power Tuning Curves

Similar effects as in Müller et al. [13] could be observed. Participants showed an individual emergence of a broad tuning curve with maxima in a range from 21 to 35 Hz, as visible in Table I. This is contrary to the findings by Tobimatsu et al. [17], who reported a narrow tuning curve with a person independent maximum at 21 Hz. The reasons for these different findings are still an open question, as Tobimatsu et al. used a different stimulator placement and a different tactile stimulation paradigm (stimulation applied to the palm, a bigger stimulation surface, and a sine modulated 128 Hz sinusoidal stimulation signal).

TABLE I

RESONANCE LIKE FREQUENCIES (F_{res}, STIMULATION FREQUENCIES AND MAXIMUM CLASSIFICATION ACCURACIES IN [%] FOR ALL PARTICIPANTS. THE STIMULATION FREQUENCY FOR THE THUMB IS F_1, THE FREQUENCY FOR THE MIDDLE FINGER F_2. THUMB AND MID. FI. (MIDDLE FINGER) REPRESENT THE ACCURACIES OF THE REFERENCE AGAINST THE RESPECTIVE CLASS. THE LAST ROW SHOWS THE ACCURACIES CLASSIFYING ATTENTION ON THE THUMB VS. ATTENTION ON THE MIDDLE FINGER (* INDICATES A VALUE ABOVE CHANCE LEVEL).

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11	s12	s13	s14	mean $\pm$ std
f_{res}	23	31	27	25	29	23	31	23	21	35	21	23	29	21	
f_1 / f_2	23/29	19/29	25/29	21/27	23/27	23/29	19/23	23/27	19/25	19/35	21/31	19/27	19/23	21/27	
thumb	74*	72*	64	76*	69*	70*	59	73*	64*	67*	63*	61*	65*	58	66.8 $\pm$ 5,7
mid fi	73*	64*	65*	78*	64*	69*	66*	72*	65*	66*	58	68*	64*	61	66.6 $\pm$ 5.1
th/mf	57	56	57	59	58	62*	62 *	60	61	60	58	56	60	59	58.6 $\pm$ 2.0

B. Classification

All participants except one performed above chance chance in at least one class vs. reference. However only two participants slightly exceeded the chance level, classifying focused attention on thumb vs. focused attention on the middle finger. This was achieved using merely a single bipolar channel over the primary sensor and motor regions of the cortex. No further optimizations like individual channel selection and channel combinations have been performed. According to [10], [11] and [12], other cortical regions are also involved in processing vibro-tactile stimulation. Therefore, different channel combinations might further increase classification accuracy, especially classifying thumb vs. middle finger. Measured electrode positions have also not been taken into account yet and could be used for source localization and electrode placement. Participants reported problems switching their attention to a specific finger. The twitches should help the participants focus on a specific finger. The importance of such twitches has to be investigated in more detail, to clarify whether twitches are useful or not. In addition, using higher harmonics for classification already significantly increased classification accuracy in SSVEP BCIs [18]. This principle could also be applied to a BCI based on SSSEP.
To sum up, the results indicate that focusing attention to some tactile stimulation on one hand can be modulated quite well, but shifting attention to a specific finger during parallel stimulation is a much more demanding task.

C. Future Works

To further increase classification accuracy, investigations regarding optimal channel selection, perhaps person specific, will be done. Including higher harmonics into the classification procedure will also be investigated, as well as the effect of twitches or modifications in the stimulation signal (e.g. amplitude).

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