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HAL Authorization

2 **Toward a SSSEP-based BCI using the sensory gating** 3 **phenomenon**

4 **José Rouillard ¹, François Cabestaing ¹, Marie-Hélène Bekaert ¹, Jean-Marc Vannobel ¹**

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8 **Abstract:** A physiological phenomenon named movement-related sensory gating has been
9 described in the literature in the late 80s. To the best of our knowledge, it has not yet been
10 exploited in the BCI domain. We consider that this phenomenon could significantly decrease the
11 resonance-like frequency of Steady State Somatosensory Evoked Potentials (SSSEP) and be
12 exploited as a voluntary command of the user will. We describe our work to retrieve a resonance
13 in user's EEG while applying vibrations under their fingers. Our first results confirm previous
14 works reported in literature concerning SSSEP. We report SSSEP detected on four healthy subjects
15 who received tactile vibration under their right and left index finger at five different frequencies
16 (14, 17, 20, 23 and 26 Hz). The mechanical stimulation was created by a device conceived in our
17 laboratory. This device is based on two C2-tactors piloted by an Arduino. We think that a
18 SSSEP-based BCI using the sensory gating phenomenon could be used soon by DMD (Duchenne
19 Muscular Dystrophy) patients that can perceive vibrations under their skin but are no more able to
20 perform voluntary movements.

21 **Keywords:** BCI; SSSEP; movement-related sensory gating; resonance-like frequency; vibration;
22 Steady State Somatosensory Evoked Potential.

23

24 **1. Introduction**

25 Since the first works on BCI (Brain-computer Interfaces) [1], it is possible to detect in EEG
26 sudden and time-locked responses to a transient event, such as the P300 evoked potential that
27 occurs 300 ms after a stimulus, for example. It is also possible to highlight in real-time steady-state
28 evoked potentials (SSEP), observable, for instance, as a brain response induced by a visual stimulus,
29 flickering at a constant frequency.

30 In this paper we present our proposition toward a new SSSEP-based BCI using the
31 movement-related sensory gating. The main idea lies in the exploitation, in the field of BCI, of the
32 physiological phenomenon known as tactile suppression phenomenon (or movement-related
33 sensory gating) [2]. During a limb movement, the brain's ability to detect tactile stimulations on the
34 moving limb is significantly reduced. Otherwise when applying a vibration on the user skin
35 (example: under fingers), a resonance at that same frequency can be detected in the EEG. Our
36 hypothesis is that the amplitude of this resonance could be affected by the sensory gating. If so, it
37 should be possible to detect this decrease in the EEG signals, for example during a finger motion
38 while vibration is applied to that finger.

39

40 For now, the movement-related sensory gating phenomenon has been described in the
41 literature [3], but, to our knowledge, has not yet been exploited as an explicit command allowing a
42 user to control a computer or robot without muscle activity, based on either a real or an imagined
43 movement. We consider that resonance decrease could be significant enough to be exploited as a
44 voluntary command of the user will.

45 The rest of the article is organized as follow: section 2 presents Steady State Evoked Potentials
 46 and how they are used in BCI; section 3 describes more deeply the sensory gating phenomenon and
 47 exposes some related work; section 4 describes the materials and methods used in our researches;
 48 and finally the results of this work are presented in section 5 and discussed in section 6.

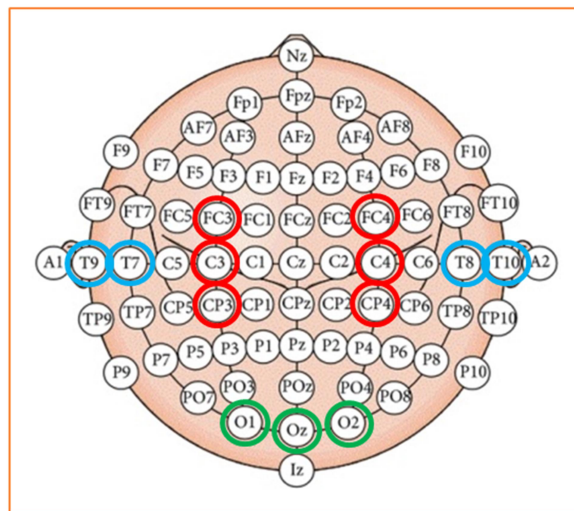
49 2. Steady State Evoked Potentials and BCI

50 In the Brain-Computer Interface domain (BCI), an Event-Related Potential (ERP) is a
 51 measurable brain electrophysiological state modification, which appears in response to either an
 52 external stimulation (image, sound, vibration...) or an internal event such as a cognitive activity
 53 (attention, motor preparation ...) [4].

54 More precisely, as described by Vidal, an evoked potential is the synchronous activity of the
 55 neurons beneath an electrode that produce a short aperiodic waveform buried under the
 56 background activity in response to a visual, auditory or somesthetic stimulus [1]. Steady-state
 57 evoked potentials reflect a sustained cortical response induced by the long-lasting periodic
 58 repetition of a sensory stimulus. These steady-state responses remain constant in amplitude and
 59 phase over time such as a kind of response or resonance to the stimulus at a particular frequency of
 60 stimulation [5].

61 In order to detect an ERP, the experimenter needs to know where, when and what to look for.
 62 After placing the electrodes at the desired locations (where to look, see Figure 1), the experimenter
 63 must prepare his material (amplifier in particular) and his software (OpenVibe, for example), in
 64 order to scan the appropriate frequencies (what to look for, see Table1). There is no important delay
 65 observed between the stimulation experienced by the user and the resonances that are observed on
 66 his EEG (when to look).

67 As explained on Figure 1, conforming to the envisaged ERP, it is necessary to place electrodes
 68 on specific location of the scalp. In the EEG International 10–20 system, among all the locations
 69 available on an EEG cap, the T (for Temporal), O (for Occipital) and C (for Central) are often used to
 70 easily locate the ERP detection.



71
 72 **Figure 1.** Blue, red and green positions for electrodes corresponding to Temporal, Central and
 73 Occipital areas, in order to detect respectively SSEAP, SSSEP and SSVEP.
 74

75 According to the literature, SSEAP (Steady State Auditory Evoked Potential) are often detected
 76 in the range 5 to 50 Hz, SSVEP (Steady State Visually Evoked Potential) in the range 3 Hz to 40 Hz,
 77 and SSSEP (Steady State Somatosensory Evoked Potential) in the range 5 to 250 Hz [6-8].

78 SSVEP signals are natural responses to visual stimulation at specific frequencies. Indeed, when
 79 the retina is excited by a visual stimulus the brain generates electrical activity at the same frequency
 80 and at one or more of its harmonics. BCIs successfully used SSVEP to control a computer cursor

81 [9]-0], an avatar [11], a robot [12-13], a wheelchair [14] or a spelling system [15-16]. SSVEP have
82 been extensively used for BCIs but they require a high level of visual attention which can be tiring
83 for the user. Indeed, the main drawback of SSVEP-based BCI paradigms is obviously the visual
84 fatigue of the user during and after repetitive (and boring) sessions where the user has to focus on a
85 flickering visual target.

86 SSAEP are detected as cerebral responses to auditory stimulation when the cochlea transmits
87 data to the cortex via the ascending auditory pathway. Such resonance can be detected in the brain
88 signal of the user listening to the repetitive sounds at a particular frequency. Auditory ERP can be
89 used in auditory speller BCI or multi-choice based BCI [17-18]. The main drawback of SSAEP is the
90 particular attention that the user must pay in order to concentrate on the active listening of the
91 emitted sounds.

92 SSSEP are detected as cerebral responses to vibratory stimulation applied on the user's body
93 (palm of the hand, wrist, finger and toe). Electrodes are positioned accordingly, for instance in C3,
94 C4, or Cz location (see Figure 1) to detect a brain signal response to a vibration applied on right
95 finger, left finger or toe, respectively. Müller-Putz and al. [19] first defined the basic SSSEP-based
96 BCI paradigm with index fingers stimulations. These potentials have been proven by Breitwieser
97 and his team [20] to be stable enough to be exploited in a brain-computer interface. The feasibility
98 of SSSEP based BCIs for wheel chair control [21-22], or task discrimination [23] was also studied.
99 SSSEP based BCIs may reduce the fatigue usually induced by visual attention required in SSVEP
100 based BCIs. They are used, for example, as communication tools dedicated in complete locked-in
101 syndrome (CLIS) patients for which SSVEP are inoperative [24]. SSSEP can be an alternative
102 approach with the use of the somatosensory evoked potentials which are triggered by the activation
103 of the mechanoreceptors on the skin. Even if it is not easy for a classical user (not blind for instance)
104 to pay attention to a particular frequency among several, felt on the body, it could however be
105 exploited in a more passive way than SSVEP and SSAEP. Indeed, one can choose to ask the user to
106 focus on a perceived vibration or not. Some publications report experiments where users were
107 isolated, acoustically, and so were not disturbed by the sound emitted by the vibration: *"Relaxing
108 music was presented via headphones to distract the subject during the whole experiment"* [25].

109 3. Movement-Related sensory Gating phenomenon and related work

110 During voluntary movement of a limb our ability to detect tactile stimuli on it is reduced. This
111 phenomenon is called "movement-related sensory gating". The stimuli (close to the limit of
112 detection at rest) can indifferently be produced by a mechanical (vibratory) or electrical stimulation.
113 This phenomenon has been observed for animals (cats [26], monkeys [27] and rats [28]) as well as
114 for humans [29-30]. Unable to handle all ascending and descending information set during
115 movement, the central nervous system ignores minor or predicted sensory information to focus on
116 the perception of new or unexpected information [29] [20].

117 In a series of three articles [31-33], Williams SR et al. have demonstrated that the tactile
118 suppression level related to simple movement depends on many parameters associated with the
119 stimulus (location, intensity) or with the movement (complexity, nature, speed). The tactile
120 suppression related to a more complex movement like goal-directed movement has also been
121 studied [34]. It seems that the determining factor of tactile suppression is the motor activity and not
122 the movement itself [35]. Tactile suppression or attenuation thus appears during an active
123 movement, a passive movement, pantomime [36] or imagined movements [37].

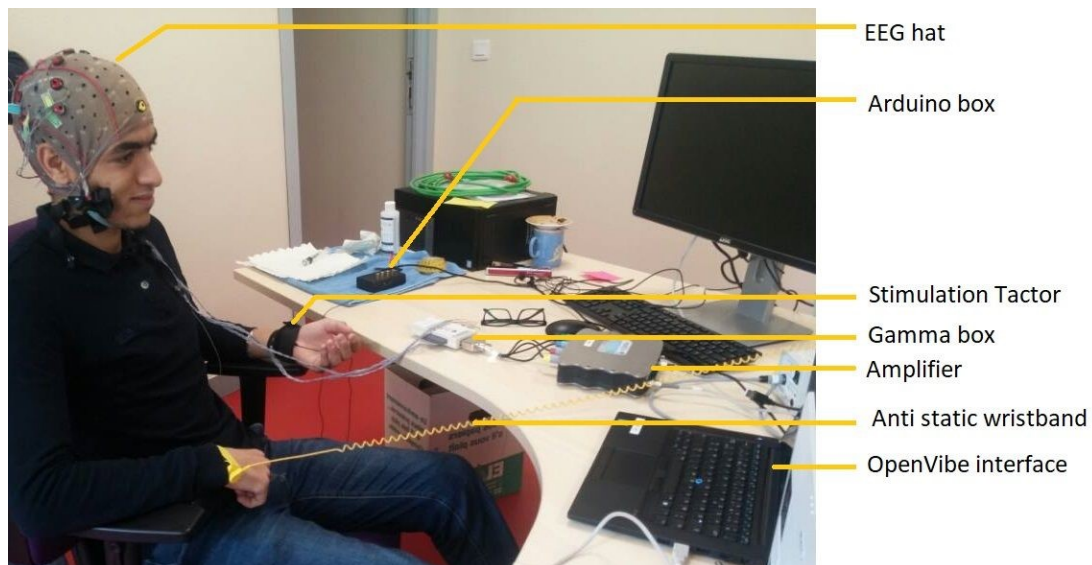
124 Chapman noticed factors influencing the transmission of somatosensory signals to primary
125 somatosensory cortex, according to active or passive touch: [38]. Some studies concluded that
126 viewing a hand performing an action or being touched interferes with the processing of
127 somatosensory information arising from the hand. It's in average a gating of 22% when the user is
128 viewing a video of a hand performing a movement, and 17% decrease when the user is observing a
129 passive touch video [39].

130 Few articles have studied the effects of mental movement imagery on tactile suppression,
131 however the results obtained [38] demonstrate that imagined self-touch is attenuated just as real

132 self-touch is. The attenuation of tactile perception decreases as the stimulus intensity increases [32].
 133 In the present study we assume that this attenuation is still sufficiently perceptible when the tactile
 134 stimulation frequency is close to the resonance frequency. We also know that the ability to
 135 discriminate minor difference in intensity of two tactile stimuli is not affected during the movement
 136 [29] [40]. So considering attenuation of tactile perception we hope in a future study discriminate a
 137 left movement of a right movement. First, we study the feasibility of a BCI based on gating with
 138 real movements. If our results prove conclusive, we will conduct a similar study with imagined
 139 movements. The following sections describe the equipment (vibratory device, EEG system), method
 140 (OpenVibe senarii for protocols) and results.

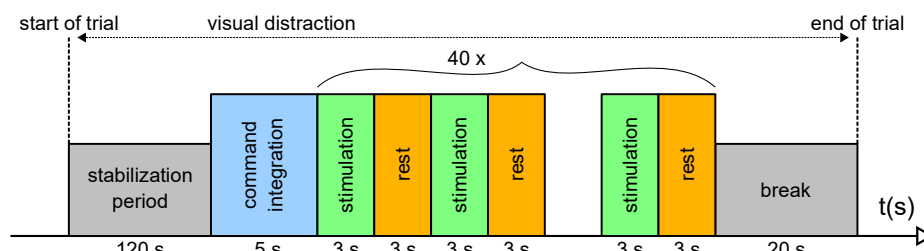
141 4. Materials and Methods

142 The hardware and software used in our experience are presented in Figure 2. The EEG cap was
 143 equipped with Ag/AgCl wet electrodes placed on FC3, FC4, CP3 and CP4 (see Figure 1). The
 144 reference electrode was placed on left ear and the ground electrode was placed on Fpz. The tactile
 145 stimulation device, a C2-tactor, (from Engineering Acoustics, Inc., Florida and USA) was controlled
 146 by an Arduino Box created by our team. The signal amplifier and sampler is from gTec (g.USBamp,
 147 particularly). The main software is Openvibe coupled with Python scripts.
 148



149 **Figure 2.** Hardware and software for our experience setup

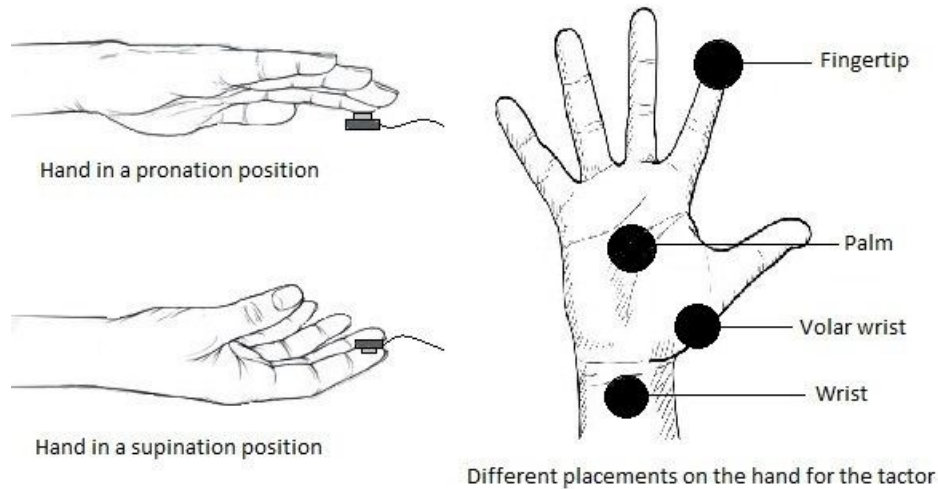
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 151
 152 Figure 3 describes our screening paradigm, adapted from [25]. A tactile stimulation was
 153 applied 40 times for 3 seconds, with a rest of 3 seconds between each stimulation on each hand of 4
 154 subjects.
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156 **Figure 3.** Screening paradigm applied in our experiment

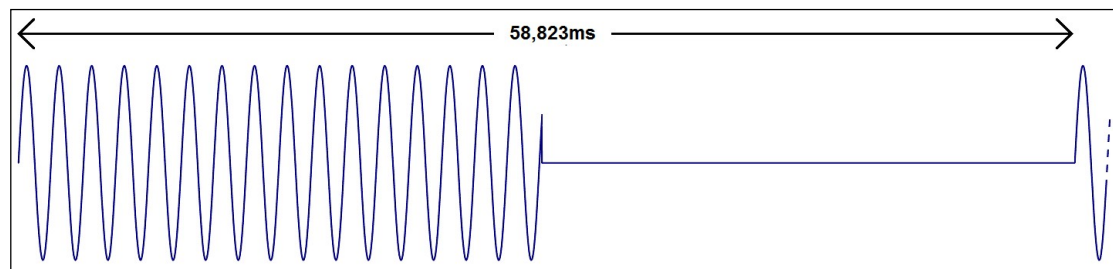
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 159 After many tries on various parts of the body, and particularly on the hands, we have chosen
 160 to apply a vibration under the users fingers in a pronation position, as we can see on Figure 4,

161 because it was perceived to be the most comfortable for users and the fastest to set up, in
 162 accordance with the physiology literature that argue that index fingertips have the most important
 163 mechanoreceptor density [41].



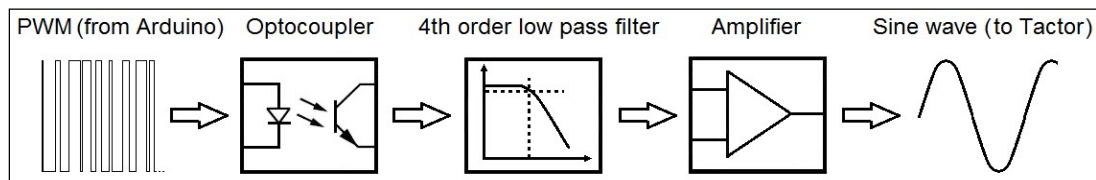
164 **Figure 4.** Various location of the hand studied to apply a tactile vibration.

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 167 During the 3 seconds stimulation periods illustrated in Figure 3, the Arduino sends low
 168 frequency pulse bundles to the Tactor stimulation devices. This pulse bundles frequency can be set to
 169 14, 17, 20, 23 or 26Hz depending on the experimental needs. Bursts are composed of a 274,12Hz sine
 170 wave and have a pulse ratio of 50%. Figure 5 shows the shape of these bursts here in case of a 17Hz
 171 frequency signal, meaning a burst period of 58,823ms. The non-integer 274,12Hz frequency used for
 172 the bursts has been defined as a compromise between the C-2 Tactor resonance frequency and the
 173 Arduino frequency division possibilities.
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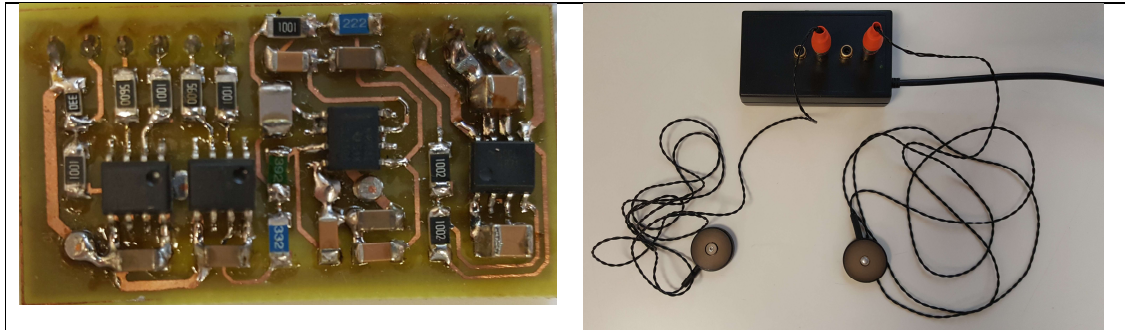
175 **Figure 5.** One period of a 17Hz burst of 274,12Hz sine wave output with a pulse ratio of 50%.

176
 177
 178 Since it is not possible to directly drive the Tactors from the Arduino, an electronics board as
 179 illustrated in Figures 6 and 7, has been built to firstly get smooth sine waves from the Arduino Pulse
 180 Width Modulation (PWM) output and secondly to amplify them with the needed power.
 181



182 **Figure 6.** Sine wave generation from a PWM input.

183
 184
 185 At last, stimulation settings are simply sent to the Arduino board via a serial monitor in
 186 accordance with the experimental paradigm.
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188 **Figure 7.** Sine wave generator electronics board (left), 2x C-2 Tactor connected to the Arduino
 189 box including the wave generators (right).

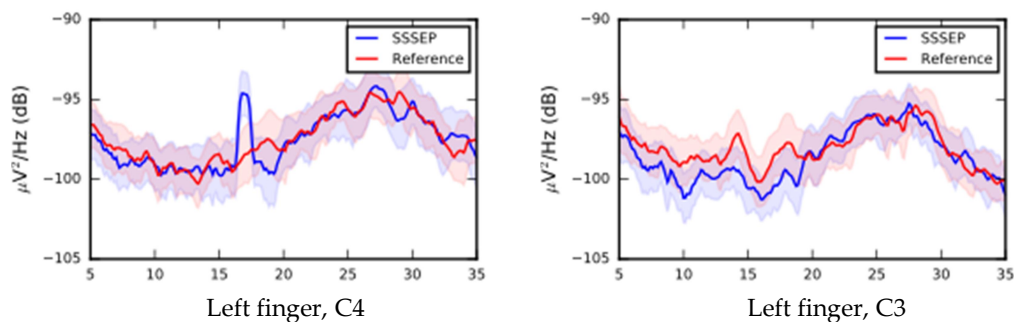
190 5. Results

191 As indicated in section 4 we used four electrodes for EEG recording. Electrodes were
 192 positioned over the primary sensorimotor cortex, at locations FC3, FC4, CP3 and CP4 (international
 193 10-20 system). EEG signals were bandpassed filtered between 0.1 and 50Hz with a Butterworth 4-th
 194 order filter and sampled at 512Hz. The four EEG signals were recorded, although only bipolar
 195 EEG-channels were processed later. In the following, C3 denotes CP3-FC3 and C4 denotes CP4-FC4.

196 Power spectral densities (PSD) of fixed-length epochs of bipolar EEG signals were computed.
 197 In each trial, i.e. for each user, each stimulation side and each stimulation frequency, we defined
 198 two sets of epochs. One set was composed of 40 epochs extracted from EEG measured during tactile
 199 stimulation, referred to as "SSSEP epochs". The other set, used to estimate the EEG baseline, was
 200 composed of 40 epochs of EEG measured with no tactile stimulation, referred to as "reference
 201 epochs". These 80 epochs were extracted from the signals recorded during the "stimulation" and
 202 "pause" periods displayed in figure 3. In order to let transient brain responses to stimuli die away,
 203 all epochs started half a second after the beginning or end of stimulation, therefore lasted only 2.5
 204 seconds. To artificially increase the PSD frequency precision, each epoch was zero-padded to 8
 205 seconds duration, i.e. 4096 samples.

206 In the following figures, PSDs are plotted for frequencies ranging from 5 to 35 Hertz. More
 207 precisely, we compute the average PSD of each set of epochs, as well as its standard deviation.
 208 Average PSDs are represented by solid curves, in red for reference epochs, in blue for SSSEP
 209 epochs. For each set, two extra curves with a lighter color indicate the interval at plus and minus
 210 half standard deviation.

211 For example, Figure 8 shows four sets of curves for a given user and a given stimulation
 212 frequency. One can observe in the upper left and bottom right figures that there is a difference
 213 between the average PSD of reference epochs and the average PSD of SSSEP epochs at the
 214 stimulation frequency (here 17Hz). This confirms the literature, since somatosensory evoked
 215 potentials can be detected mainly in signals recorded on electrodes contralateral to the stimulated
 216 finger, i.e. C4 for a stimulation of the left finger and C3 for a stimulation of the right finger. In the
 217 following, we will not present the PSDs of signals recorded by electrodes ipsilateral to the
 218 stimulated finger.
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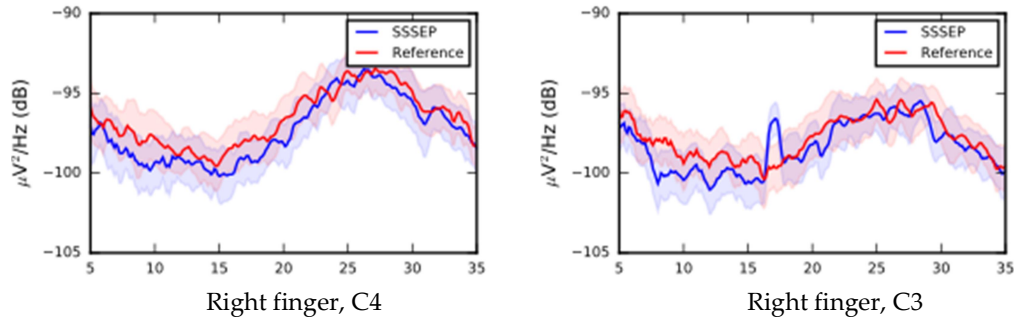
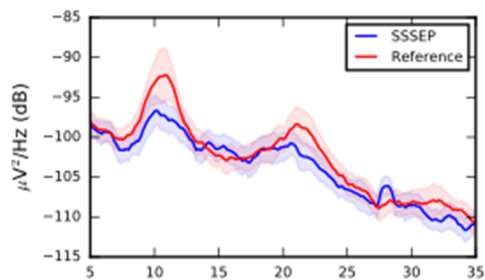


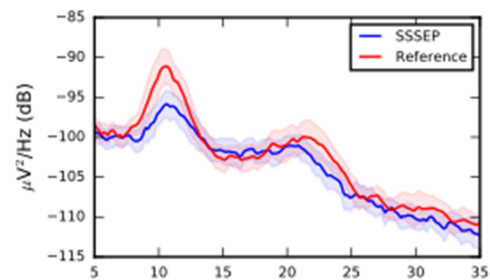
Figure 8. Subject number 3, stimulation frequency 17Hz.

All the results, i.e. SSSEP vs. reference average PSDs for each user, each stimulation side and each stimulation frequency are presented in appendix A. Several interesting situations are presented in Figure 9. In Figure 9(a), the right finger of user #1 was stimulated at 14~Hz. Although no SSSEP appears for this frequency, one can observe that a SSSEP is visible for 28~Hz, which is the first harmonic of the stimulation frequency. On the same figure, and on many sets of curves represented for the same user (such as Figure 9(b)), one can also observe that there is a significant difference between SSSEP and reference PSDs around 10 Hz and 22 Hz. We hypothesize that this could correspond to an event-related desynchronization of mu and beta rhythms caused by an involuntary contraction of the hand or finger. Unfortunately, we did not record EMG during this experiment, which could have been useful to verify this hypothesis.

Figure 9(c) shows SSSEP vs. reference PSDs for user #3 for a stimulation of the right finger at 14 Hz. A difference appears between the two solid curves, but the outer lighter curves clearly overlap. In this case, we consider that the difference is not statistically significant, which implies that detecting the SSSEP "online", using for example a threshold, could be problematic. Figure 9(d) shows the curves for the same user and the same frequency, but for stimulation on the other hand. Here, the difference appears to be statistically significant, since the average values differ by more than one standard deviation.



(a) Subject 1, 14 Hz stimulation, right finger



(b) Subject 1, 17 Hz stimulation, left finger

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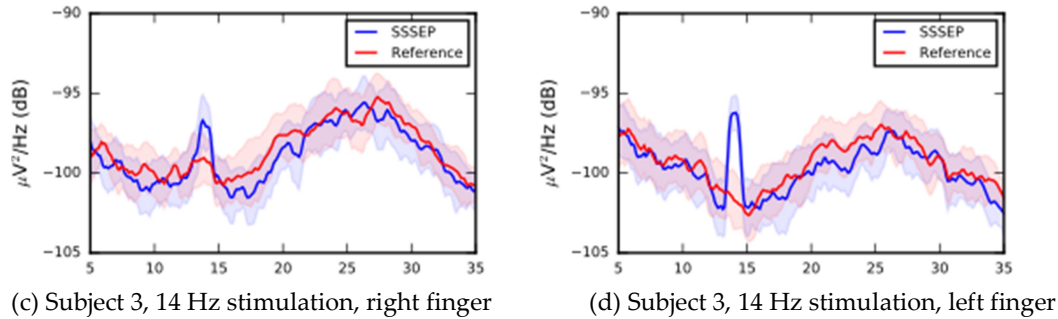


Figure 9. SSSEP vs. reference PSDs for a few specific cases.

255 6. Discussion

256 A large majority of BCI approaches exploiting Steady State Evoked Potentials (SSEP) rely on
 257 the ability of the user to focus his attention on the stimulus. When repetitive visual or auditory
 258 stimuli are involved (resp. in SSVEP- or SSAEP-based BCIs), in fact attention focusing is the only
 259 action that allows the user to voluntarily modulate his brain activity, therefore to control the
 260 interface. It has been shown that attention focusing could also be the paradigm in a SSSEP-based
 261 BCI [19-23]. We think that another approach to SSSEP-based BCI could be to exploit the
 262 movement-related sensory gating phenomenon. This paradigm would not imply attention focusing,
 263 since movement-related sensory gating is an endogenous phenomenon. This could be an interesting
 264 alternative and it would be interesting to study the users' fatigue or loss of attention in this case.

265 A second difference between a "gating"-based BCI and focus of attention SSSEP-, SSVEP- and
 266 SSAEP-based BCIs concerns the characteristics of the signal presents in the subject's EEG. As seen,
 267 the searched information present at rest is a sharp spike that is expected to disappear when the
 268 subject makes a movement, and this spike is not related to Beta and Mu waves that moreover vary
 269 from a subject to another. The spike we speak about precisely corresponds to a physiological
 270 response of the subject matching with the pulse bundles frequency and called resonance-like, 17Hz
 271 for instance, so only with the vibrating stimulation. This is then really interesting since we know in
 272 advance which resonance-like frequency bandwidth to precisely use for a given subject receiving a
 273 well-controlled stimulation.

274 In this study we placed the C2-Tactors on fingertips. To further improve the power of the
 275 stimulation frequency present in the EEG, a more detailed study is also required to determine the
 276 best stimulation devices location and touching position relatively to the kind of sensory
 277 mechanoreceptors particularly involved in the gating phenomenon (Meissner, Merkel, Pacini and
 278 Ruffini corpuscles) [25], and the hand area (fingertips, wrists, etc.) where to find them in number
 279 [42].

280 First results also show the absence of stimulation frequency peaks in the EEG of certain
 281 subjects. It is important to question their origin. Thus, parallel EMG measurements have to done to
 282 support or reject the existence of involuntary or uncontrollable hand or fingers movements during
 283 the tests.

284 Other concerns to take into account are the EEG headset design to make it more comfortable
 285 knowing that only two pairs of electrodes are sufficient to proceed with the proposed technique,
 286 also the possibility to use a "gating" phenomenon based BCI in a noisy or disturbing environment,
 287 at home and or at work. For instance, the "gating" phenomenon as a way to interact with the
 288 environment could be very interesting for disabled people with severe muscular disorders such as
 289 Muscular Dystrophy.

290 7. Conclusions

291 Our purpose was to introduce, in the BCI domain, a new possible way to interact thanks to a
 292 physiological phenomenon named motion-related sensory gating. This had already been described

293 in the literature but not yet been exploited. We have developed the hardware and software aspects
294 in order to achieve this goal. Our C2-tactors (piloted by a specific box created in our lab, containing
295 an Arduino card) are generating effectively some vibrations at a certain frequency, emitted under
296 the fingers of users. We successfully retrieved in EEG the expected resonances when users were
297 inactive (SSSEP). We are now preparing new experiments in order to detect some resonance
298 decrease in SSSEP that could be significant enough to be exploited as a voluntary command of the
299 user will. In other words, we are expecting a user to interact with a machine by thinking of
300 performing a small finger movement meanwhile a vibration is emitted under this finger. This new
301 method of BCI interaction could be useful in situations where users are not enough strong to
302 perform a finger movement (Duchenne Muscular Dystrophy patients for instance) but where an
303 intention to perform this movement is still detectable.

304 **Author Contributions:** Conceptualization, Jose Rouillard and Francois Cabestaing; Investigation, Marie-helene
305 Bekaert; Methodology, Jose Rouillard and Francois Cabestaing; Resources, Jean-marc Vannobel; Software, Jose
306 Rouillard; Validation, Francois Cabestaing; Writing – original draft, Jose Rouillard, Francois Cabestaing,
307 Marie-helene Bekaert and Jean-marc Vannobel; Writing – review & editing, Jose Rouillard, Francois
308 Cabestaing, Marie-helene Bekaert and Jean-marc Vannobel.

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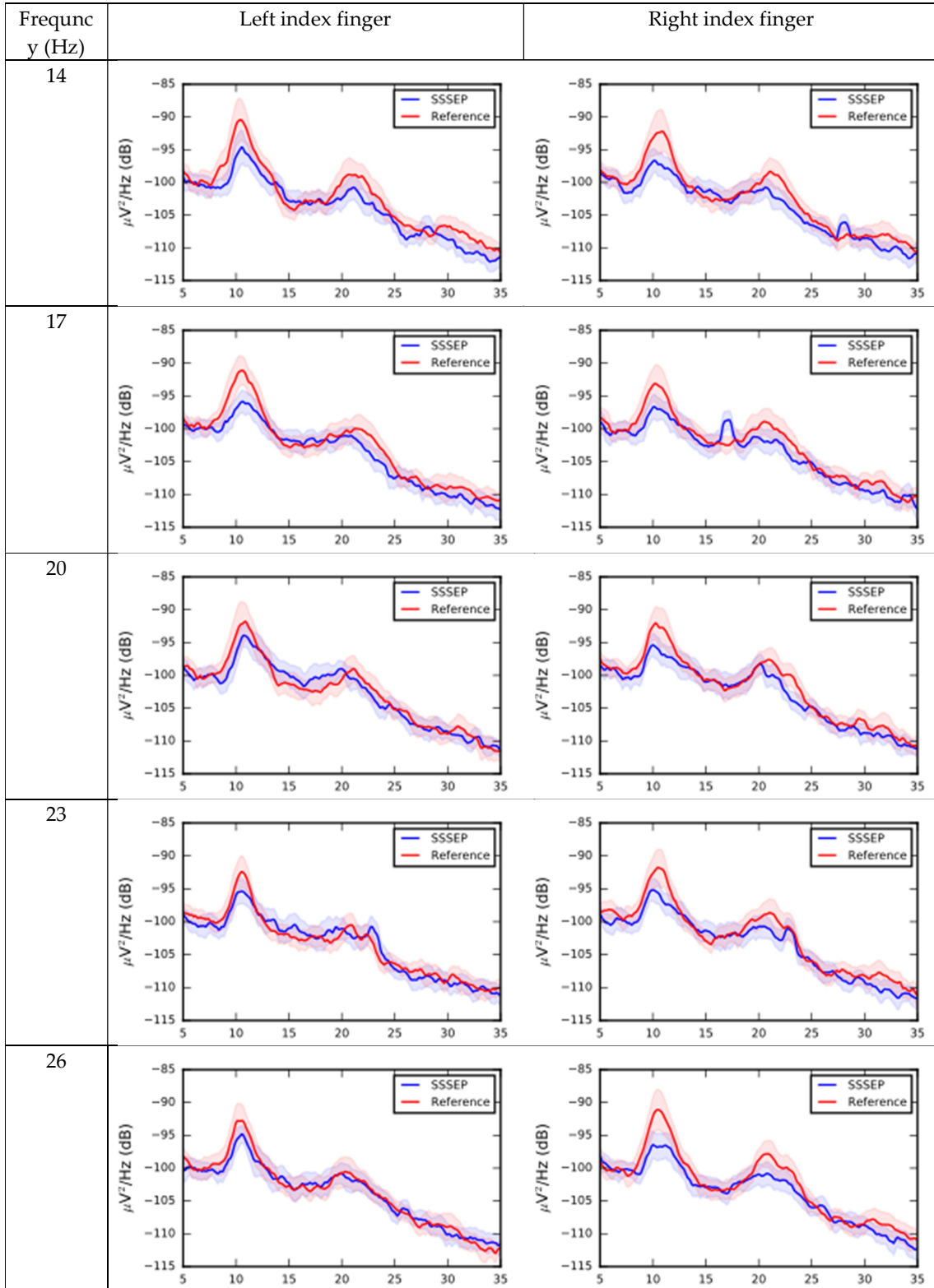
310 **Acknowledgments:** The authors would like to thank the students that have been involved in this work:
311 Oussama Saddouk and Smeety Pramij.

312 **Conflicts of Interest:** The authors declare no conflict of interest.

313

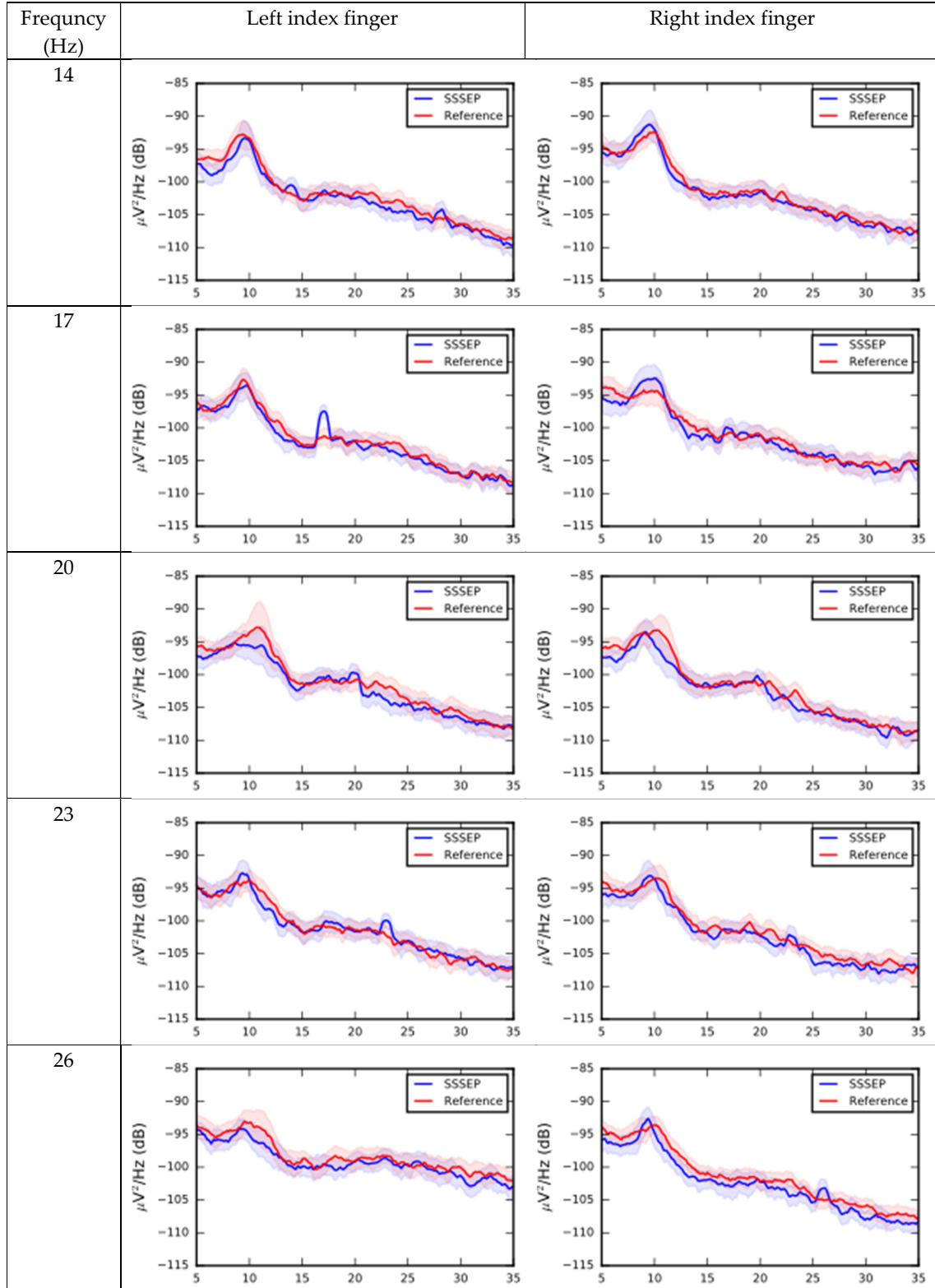
314 **Appendix A**

315 **Table A1.** Subject 1, SSSEP (blue) and reference signal (red), for left index finger (left column) and
 316 right index finger (right column), at the frequencies: 14, 17, 20, 23 and 26 Hz (from top to bottom)



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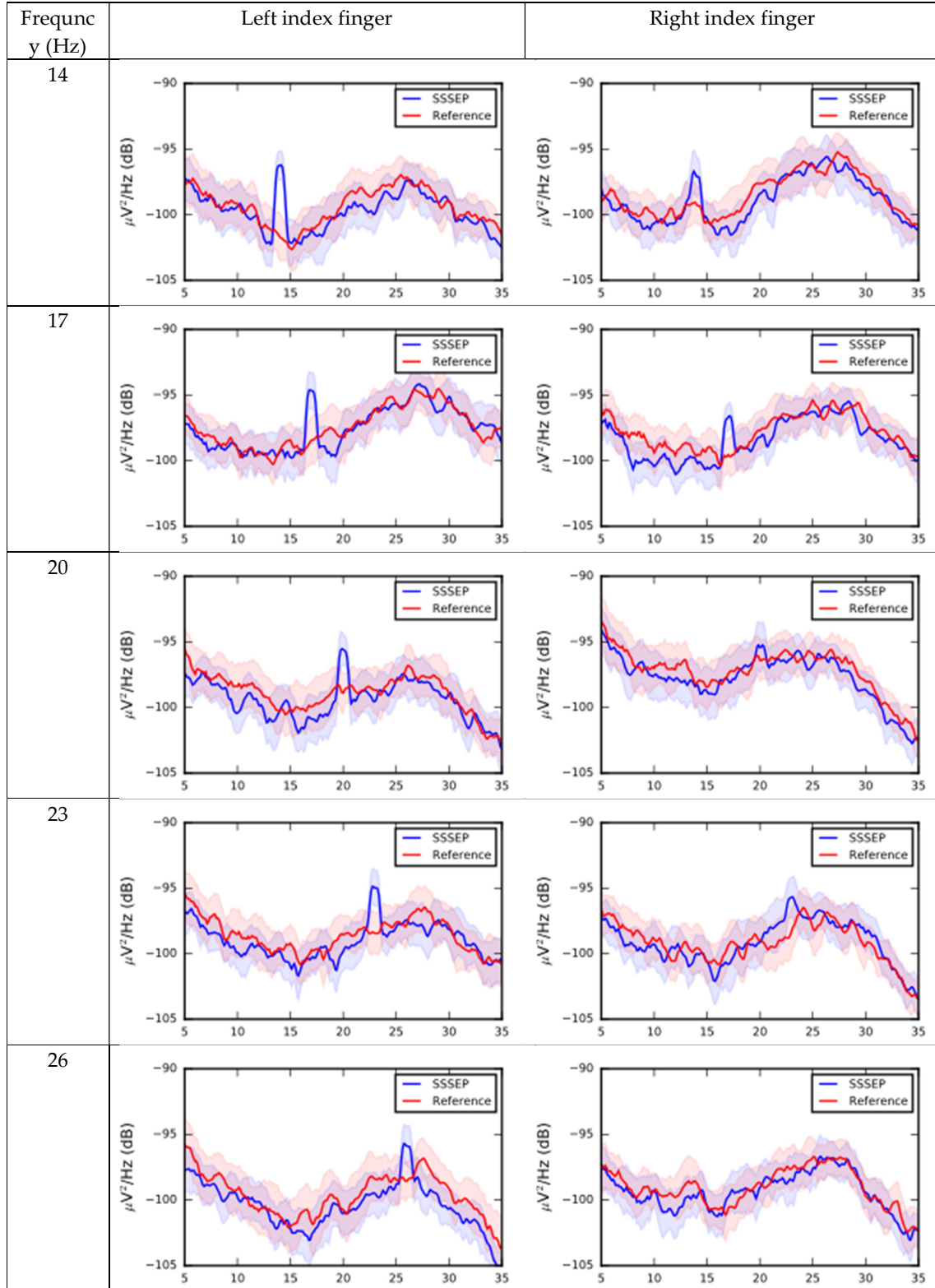
Table A2. Subject 2, SSSEP (blue) and reference signal (red), for left index finger (left column) and right index finger (right column), at the frequencies: 14, 17, 20, 23 and 26 Hz (from top to bottom)



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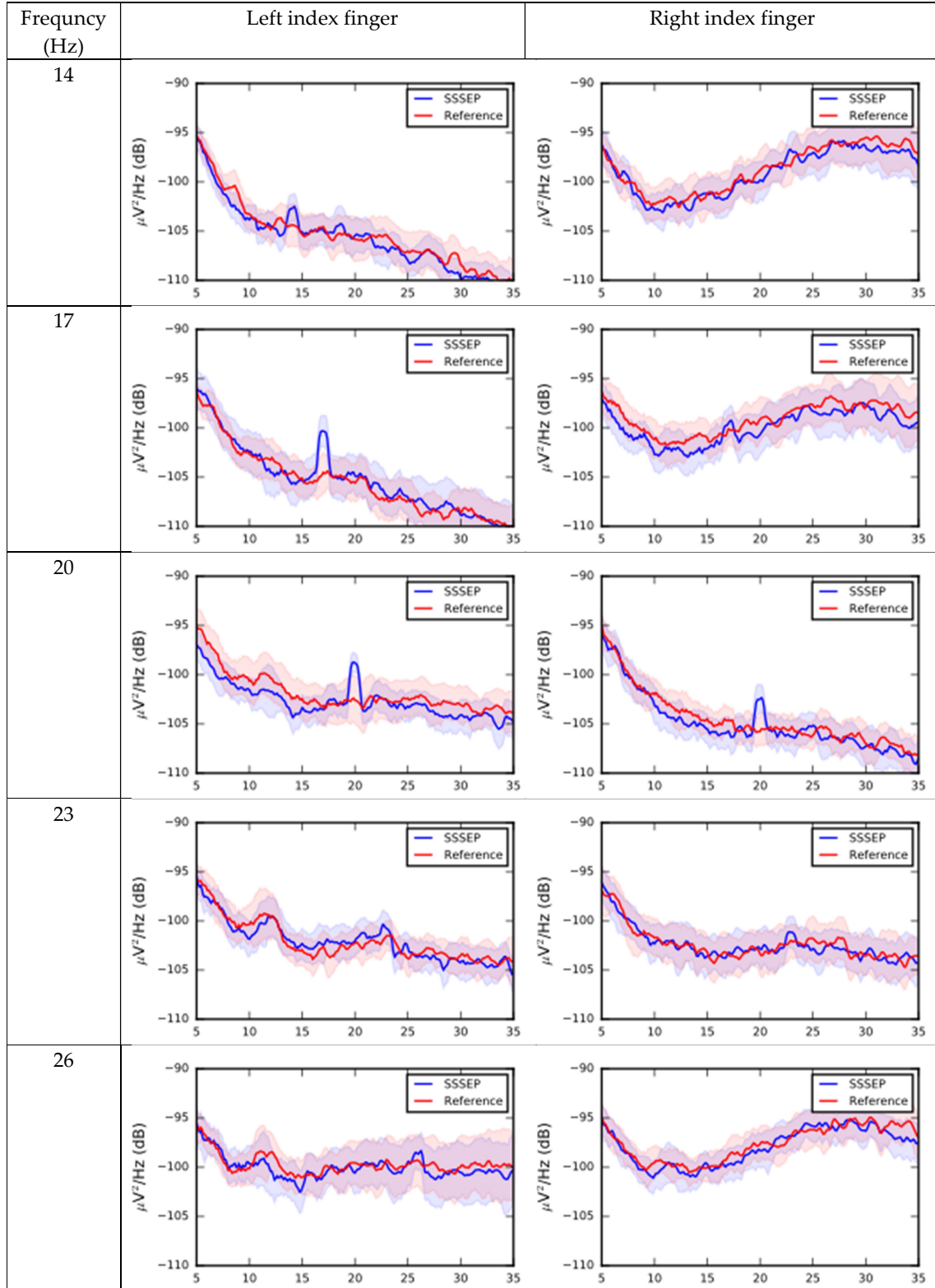
Table A3. Subject 3, SSSEP (blue) and reference signal (red), for left index finger (left column) and right index finger (right column), at the frequencies: 14, 17, 20, 23 and 26 Hz (from top to bottom)



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Table A4. Subject 4, SSSEP (blue) and reference signal (red), for left index finger (left column) and right index finger (right column), at the frequencies: 14, 17, 20, 23 and 26 Hz (from top to bottom)



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