Journal Of Clinical Neurology, Neurosurgery And Spine

Special Issue Article "Electroencephalography" Review Article

Toward a SSSEP-Based BCI Using the Sensory Gating Phenomenon

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

University of Lille, France

ARTICLE INFO

Received Date: June 01, 2022
Accepted Date: June 30, 2022
Published Date: July 01, 2022

KEYWORDS

BCI; SSSEP
Movement-related sensory gating
Resonance-like frequency
Fibration
Steady state somatosensory evoked potential

Citation for this article: José Rouillard, François Cabestaing, Marie-Hélène Bekaert and Jean-Marc Vannobel. Toward a SSSEP-Based BCI Using the Sensory Gating Phenomenon. Journal Of Clinical Neurology, Neurosurgery And Spine. 2022; 4(1):127

Corresponding author:
José Rouillard,
University of Lille, CRIStAL- Center for Research in Signal and Automatic Computing of Lille, France,
Email: jose.rouillard@univ-lille.fr

ABSTRACT

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

INTRODUCTION

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

In this paper we present our proposition toward a new SSSEP-based BCI using the movement-related sensory gating. The main idea lies in the exploitation, in the field of BCI, of the physiological phenomenon known as tactile suppression phenomenon (or movement-related sensory gating) [2]. During a limb movement, the brain's ability to detect tactile stimulations on the moving limb is significantly reduced. Otherwise when applying a vibration on the user skin (example: under fingers), a resonance at that same frequency can be detected in the EEG. Our hypothesis is that the amplitude of this resonance could be affected by the sensory gating. If so, it should be possible to detect this decrease in the EEG signals, for example during a finger motion while vibration is applied to that finger. For now, the movement-related sensory gating phenomenon has been described in the literature [3], but, to our knowledge, has not yet been exploited as an explicit command allowing a user to control a computer or robot without muscle activity, based on either a real or an imagined movement. We consider that resonance decrease could be significant enough to be exploited as a voluntary command of the user will. The rest of the article is organized as follow: section 2 presents Steady State Evoked Potentials and how they are used in BCI; section 3 describes more deeply the sensory gating phenomenon and exposes some related work; section 4 describes the materials and methods used in our researches; and finally the results of this work are presented in section 5 and discussed in section 6.

STEADY STATE EVOKED POTENTIALS AND BCI

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

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

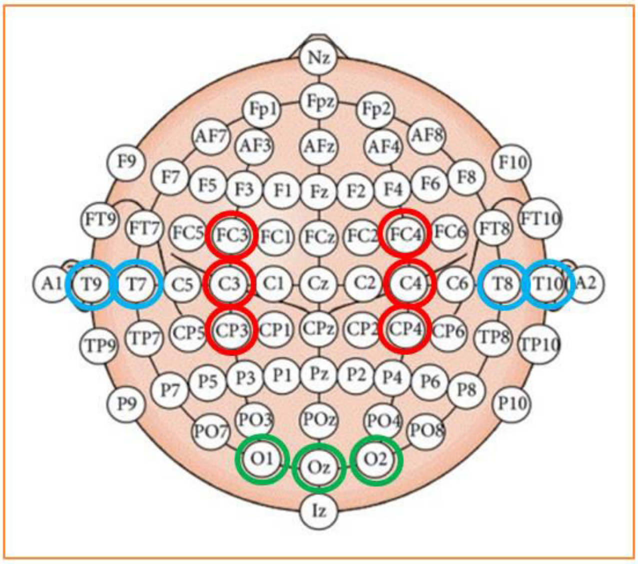


Figure 1: Blue, red and green positions for electrodes corresponding to Temporal, Central and Occipital areas, in order to detect respectively SSEAP, SSSEP and SSVEP.

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

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

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

SSVEP signals are natural responses to visual stimulation at specific frequencies. Indeed, when the retina is excited by a visual stimulus the brain generates electrical activity at the same frequency and at one or more of its harmonics. BCIs successfully used SSVEP to control a computer cursor [9,10], an avatar [11], a robot [12,13], a wheelchair [14] or a spelling system [15,16]. SSVEP have been extensively used for BCIs but they require a high level of visual attention which can be tiring for the user. Indeed, the main drawback of SSVEP-based BCI paradigms is obviously the visual fatigue of the user during and after repetitive (and boring) sessions where the user has to focus on a flickering visual target.

SSAEP are detected as cerebral responses to auditory stimulation when the cochlea transmits data to the cortex via the ascending auditory pathway. Such resonance can be detected in the brain signal of the user listening to the repetitive sounds at a particular frequency. Auditory ERP can be used in auditory speller BCI or multi-choice based BCI [17,18]. The main drawback of SSAEP is the particular attention that the user must pay in order to concentrate on the active listening of the emitted sounds. SSSEP are detected as cerebral responses to vibratory stimulation applied on the user's body (palm of the hand, wrist, finger and toe). Electrodes are positioned accordingly, for instance in C3, C4, or Cz location (Figure 1) to detect a brain signal response to a vibration applied on right finger, left finger or toe, respectively. Müller-Putz and al. [19] first defined the basic SSSEP-based BCI paradigm with index fingers stimulations. These potentials have been proven by Breitwieser and his team [20] to be stable enough to be exploited in a brain-computer interface. The feasibility of SSSEP based BCIs for wheel chair control [21,22], or task discrimination [23] was also studied. SSSEP based BCIs may reduce the fatigue usually induced by visual attention required in SSVEP based BCIs. They are used, for example, as communication tools dedicated in Complete Locked-In Syndrome (CLIS) patients for which SSVEP are inoperative [24]. SSSEP can be an alternative approach with the use of the somatosensory evoked potentials which are triggered by the activation of the mechanoreceptors on the skin. Even if it is not easy for a classical user (not blind for instance) to pay attention to a particular frequency among several, felt on the body, it could however be exploited in a more passive way than SSVEP and SSAEP. Indeed, one can choose to ask the user to focus on a perceived vibration or not. Some publications report experiments where users were isolated, acoustically, and so were not disturbed by the sound emitted by the vibration: “Relaxing music was presented via headphones to distract the subject during the whole experiment” [25].

MOVEMENT-RELATED SENSORY GATING PHENOMENON AND RELATED WORK

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

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

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

Few articles have studied the effects of mental movement imagery on tactile suppression, however the results obtained [38] demonstrate that imagined self-touch is attenuated just as real self-touch is. The attenuation of tactile perception decreases as the stimulus intensity increases [32]. In the present study we assume that this attenuation is still sufficiently perceptible when the tactile stimulation frequency is close to the resonance frequency. We also know that the ability to discriminate minor difference in intensity of two tactile stimuli is not affected during the movement [29,40]. So considering attenuation of tactile perception we hope in a future study discriminate a left movement of a right movement. First, we study the feasibility of a BCI based on gating with real movements. If our results prove conclusive, we will conduct a similar study with imagined movements. The following sections describe the equipment (vibratory device, EEG system), method (Open Vibe senarii for protocols) and results.

MATERIALS AND METHODS

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

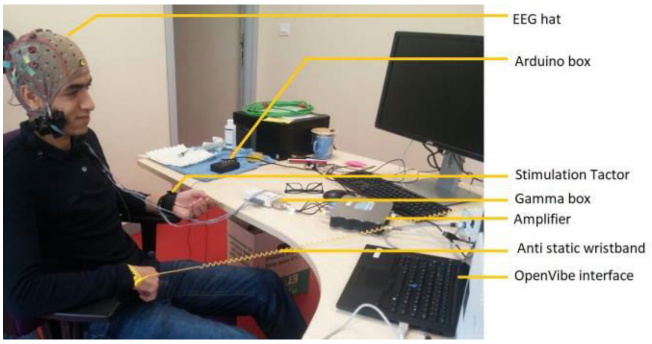


Figure 2: Hardware and software for our experience setup.

Figure 3 describes our screening paradigm, adapted from [25]. A tactile stimulation was applied 40 times for 3 seconds, with a rest of 3 seconds between each stimulation on each hand of 4 subjects.

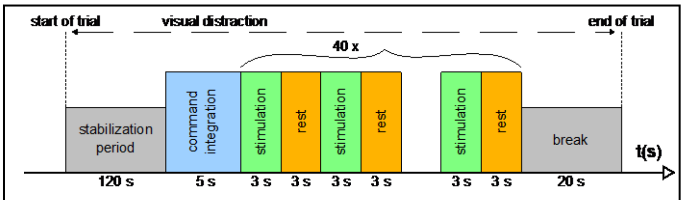


Figure 3: Screening paradigm applied in our experiment.

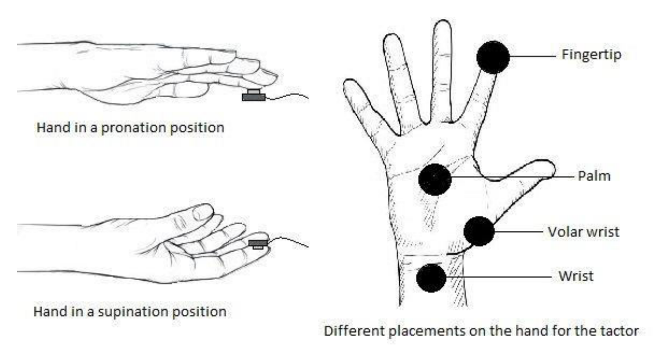


Figure 4: Various location of the hand studied to apply a tactile vibration.

After many tries on various parts of the body, and particularly on the hands, we have chosen to apply a vibration under the users fingers in a pronation position, as we can see on Figure 4, because it was perceived to be the most comfortable for users and the fastest to set up, in accordance with the physiology literature that argue that index fingertips have the most important mechanoreceptor density [41].

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

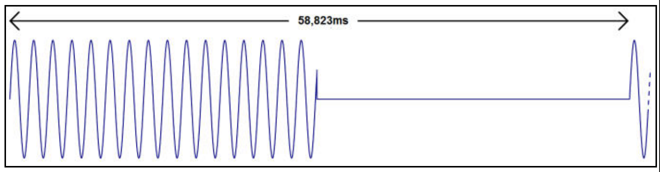


Figure 5: One period of a 17Hz burst of 274,12Hz sine wave output with a pulse ratio of 50%.

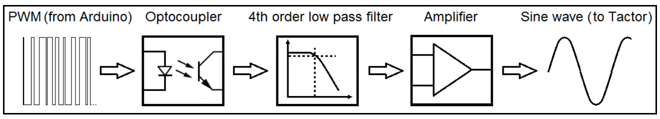


Figure 6: Sine wave generation from a PWM input.

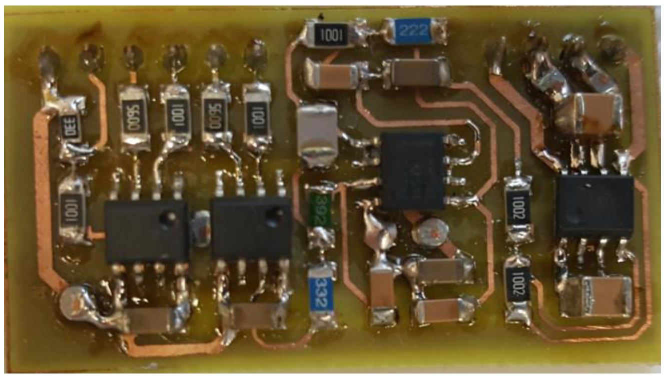


Figure 7: Sine wave generator electronics board (left), 2x C-2 Tactor connected to the Arduino box including the wave generators (right).

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

At last, stimulation settings are simply sent to the Arduino board via a serial monitor in accordance with the experimental paradigm.

RESULTS

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

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

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

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

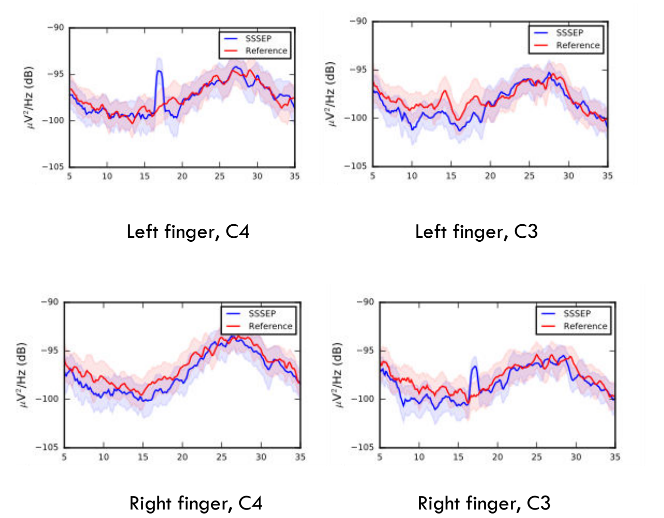


Figure 8: Subject number 3, stimulation frequency 17Hz.

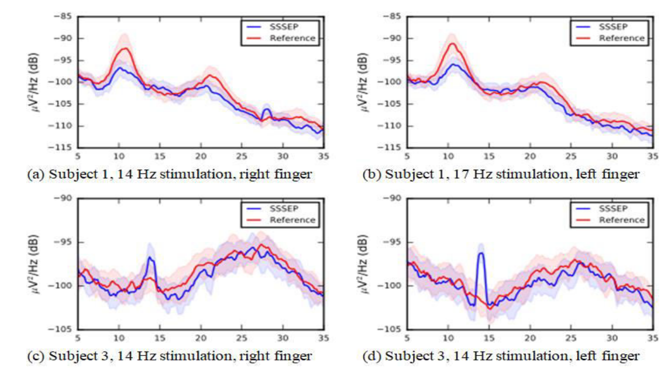


Figure 9: SSSEP vs. reference PSDs for a few specific cases.

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 9a), 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 (Figure 9b), 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 9c) 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 9d) 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.

DISCUSSION

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

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

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

First results also show the absence of stimulation frequency peaks in the EEG of certain subjects. It is important to question their origin. Thus, parallel EMG measurements have to done to support or reject the existence of involuntary or uncontrollable hand or fingers movements during the tests. Other concerns to take into account are the EEG headset design to make it more comfortable knowing that only two pairs of electrodes are sufficient to proceed with the proposed technique, also the possibility to use a "gating" phenomenon based BCI in a noisy or disturbing environment, at home and or at work. For instance, the "gating" phenomenon as a way to interact with the environment could be very interesting for disabled people with severe muscular disorders such as Muscular Dystrophy.

CONCLUSIONS

Our purpose was to introduce, in the BCI domain, a new possible way to interact thanks to a physiological phenomenon named motion-related sensory gating. This had already been described in the literature but not yet been exploited. We have developed the hardware and software aspects in order to achieve this goal. Our C2-tactors (piloted by a specific box created in our lab, containing an Arduino card) are generating effectively some vibrations at a certain frequency, emitted under the fingers of users. We successfully retrieved in EEG the expected resonances when users were inactive (SSSEP). Our preliminary results show that the effect of SSSEP varies among different subjects. The SSSEP of subjects 1 and 2 was weaker than that of subjects 3 and 4. Obviously, we will very soon increase the number of subjects to assess whether SSSEP can make a statistical difference to achieve a SSSEP-based BCI. We are now preparing new experiments in order to detect some resonance decrease in SSSEP that could be significant enough to be exploited as a voluntary command of the user will. In other words, we are expecting a user to interact with a machine by thinking of performing a small finger movement meanwhile a vibration is emitted under this finger. This new method of BCI interaction could be useful in situations where users are not enough strong to perform a finger movement (Duchenne Muscular Dystrophy patients for instance) but where an intention to perform this movement is still detectable.

AUTHOR CONTRIBUTIONS

Conceptualization, Jose Rouillard and Francois Cabestaing; Investigation, Marie-helene Bekaert; Methodology, Jose Rouillard and Francois Cabestaing; Resources, Jean-marc Vannobel; Software, Jose Rouillard; Validation, Francois Cabestaing; Writing – original draft, Jose Rouillard, Francois Cabestaing, Marie-helene Bekaert and Jean-marc Vannobel; Writing – review & editing, Jose Rouillard, Francois Cabestaing, Marie-helene Bekaert and Jean-marc Vannobel.

FUNDING

This research received no external funding.

ACKNOWLEDGMENTS

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

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Vidal J. (1973). Toward Direct Brain-Computer Communication. Annual Review of Biophysics and Bio-engineering. 2: 157-180.
2. Cheron G, Borenstein S. (1987). Specific gating of the early somatosensory evoked potentials during active movement. Electroencephalography and Clinical Neurophysiology. 67: 537-548.
3. Rushton DN, Rothwell JC, Craggs MD. (1981). Gating of somatosensory evoked potentials during different kinds of movement in man. Brain. 104: 465-491.
4. Luck SJ. (2005). An Introduction to the Event-Related Potential Technique. The MIT Press, Cambridge. ISBN: 9780262621960.
5. Colon E, Legrain V, Mouraux A. (2012). Steady-state evoked potentials to study the processing of tactile and nociceptive somatosensory input in the human brain. Neurophysiologie Clinique/Clinical Neurophysiology. 42: 315-323.
6. Rouillard J, Cabestaing F, Vannobel JM, Bekaert MH. (2018). Supervising SSSEP experiments with a Bluetooth Android remote control application. International Conference on Applied Human Factors and Ergonomics. 365-375.
7. Vialatte FB, Maurice M, Dauwels J, Cichocki A. (2010). Steady-state visually evoked potentials: Focus on essential paradigms and future perspectives. Progress in Neurobiology. 90: 418-438.
8. Cabestaing F, Derambure P, Clerc M, Bougrain L, Lotte F. (2016). Physiological Markers for Controlling Active and Reactive BCIs. Brain-Computer Interfaces 1: Foundations and Methods. Wiley Online Library.
9. Luzheng B, Jinling L, Ke J, Ru L, Yili L. (2014). A speed and direction-based cursor control system with P300 and SSVEP. Biomedical Signal Processing and Control. 14: 126-133.
10. Trejo LJ, Rosipal R, Matthews B. (2006). Brain-computer interfaces for 1-D and 2-D cursor control: designs using volitional control of the EEG spectrum or steady-state visual evoked potentials. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 14: 225-229.
11. Faller J, Muller-Putz G, Schmalstieg D, Pfurtscheller G. (2010). An application framework for controlling an avatar in a desktop-based virtual environment via a software SSVEP brain–computer interface. Presence: Teleoperators and Virtual Environments. 19: 25-34.
12. Deng Z, Li X, Zheng K, Yao W. (2011). A Humanoid Robot Control System with SSVEP-based Asynchronous. Brain-Computer Interface.Robot. 33: 129-135.
13. Prueckl R, Guger C. (2009). A Brain-Computer Interface Based on Steady State Visual Evoked Potentials for Controlling a Robot. Cabestany J, Sandoval F, Prieto A, Corchado JM. (Eds) Bio-Inspired Systems: Computational and Ambient Intelligence. IWANN, LNCS, Heidelberg. 690-697.
14. Achic F, Montero J, Penaloza C, Cuellar F. (2016). Hybrid BCI System to Operate an Electric Wheelchair and a Robotic Arm for Navigation and Manipulation Tasks. IEEE

International Workshop on Advanced Robotics and its Social Impacts (ARSO). Shanghai.

15. Vilic A, Kjaer TW, Thomsen CE, Puthusserypady S, Sorensen HB. (2013). DTU BCI speller: An SSVEP-based spelling system with dictionary support. Annu Int Conf IEEE Eng Med Biol Soc. 2212-2215.
16. Combaz A, Chatelle C, Robben A, Vanhoof G, Goeleven A, et al. (2013). A Comparison of Two Spelling Brain-Computer Interfaces Based on Visual P3 and SSVEP in Locked-In Syndrome. PLoS One. 8: e73691.
17. Höhne J, Schreuder M, Blankertz B, Tangermann M. (2011). A novel 9-class auditory ERP paradigm driving a predictive text entry system. Frontiers in Neuroscience. 5: 99.
18. Kim DW, Hwang HJ, Lim JH, Lee YH, Im CH, et al. (2011). Classification of selective attention to auditory stimuli: Toward vision-free brain-computer interfacing. Journal of Neuroscience Methods. 197: 180-185.
19. Müller-Putz GR, Scherer R, Neuper C, Pfurtscheller G. (2006). Steady-state somatosensory evoked potentials: Suitable brain signals for brain computer interfaces?. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 14: 30-37.
20. Breitwieser C, Kaiser V, Neuper C, Müller-Putz G. (2012). Stability and distribution of steady-state somatosensory evoked potentials elicited by vibro-tactile stimulation. Medical & Biological Engineering & Computing. 50: 347-357.
21. Kaufmann T, Herweg A, Kübler A. (2014). Toward brain-computer interface based wheelchair control utilizing tactually-evoked event-related potentials. Journal of Neuro Engineering And Rehabilitation. 11: 7.
22. Kim KT, Suk HI, Lee SW. (2018). Commanding a Brain-Controlled Wheelchair using Steady-State Somatosensory Evoked Potentials. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 26: 654-665.
23. Ahn S, Jun SC. (2012). Feasibility of hybrid BCI using ERD- and SSSEP- BCI. 12th International Conference on Control, Automation and Systems.
24. Guger C, Spataro R, Allison BZ, Heilinger A, Ortner R, et al. (2017). Complete Locked-in and Locked-in Patients: Command Following Assessment and Communication with Vibro-Tactile P300 and Motor Imagery Brain-Computer Interface Tools. Frontiers in Neuroscience. 11: 251.
25. Pokorny C, Breitwieser C, Muller-Putz G. (2014). A Tactile Stimulation Device for EEG Measurements in Clinical Use. IEEE Transactions on Biomedical Circuits and Systems. 8: 305-312.
26. Ghez C, Lenzi GL. (1971). Modulation of sensory transmission in cat lemniscal system during voluntary movement. Pflügers Archive. 323: 273-278.
27. Chapman CE, Rispal-Padel L, Parent MT, Lamarre Y. (1984). Gating of lemniscal input at thalamic and cortical levels during conditioned arm movements in the monkey. Abstr Soc Neurosci. 10: 735.
28. Fanselow EE, Nicolelis MA. (1999). Behavioral modulation of tactile responses in the rat somatosensory system.Journal of Neuroscience. 19: 7603-7616.
29. Chapman CE, Bushnell MC, Miron D, Duncan GH, Lund JP. (1987). Sensory perception during movement in man. Experimental Brain Research. 68: 516-524.
30. Collins DF, Cameron T, Gillard DM, Prochazka A. (1998). Muscular sense is attenuated when humans move. Journal of Physiology (London). 508: 635-643.
31. Williams SR, Shenesa J, Chapman CE. (1998). Time course and magnitude of movement-related gating of tactile detection in humans. I. Importance of stimulus location. Journal of Neurophysiology. 79: 947-963.
32. Williams SR, Chapman CE. (2000). Time course and magnitude of movement-related gating of tactile detection in humans. II. Effects of stimulus intensity. Journal of Neurophysiology. 84: 863-875.
33. Williams SR, Chapman CE. (2002). Time course and magnitude of movement-related gating of tactile detection in humans. III. Effect of motor tasks. Journal of Neurophysiology. 88: 1968-1979.
34. Juravle G, Binsted G, Spence C. (2017). Tactile suppression in goal-directed movement. Psychonomic Bulletin and Review. 24: 1060-1076.
35. Chapman CE, Tremblay F. (2015). Tactile suppression. Scholarpedia. 10: 7953.
36. Manzone DM, Ingli JT, Franks IM, Chua R. (2018). Relevance-dependent modulation of tactile suppression

during active, passive and pantomime reach-to-grasp movements. Behavioural Brain Research. 339: 93-105.

37. Kilteni K, Jan Andersson B, Houborg C, Henrik Ehrsson H. (2018). Motor imagery involves predicting the sensory consequences of the imagined movement. Nature Communications. 9: 1617.
38. Chapman CE. (1994). Active versus passive touch: factors influencing the transmission of somatosensory signals to primary somatosensory cortex. Canadian Journal of Physiology and Pharmacology. 72: 558-570.
39. Voisin J, Rodrigues E, Hétu S, Jackson P, Vargas C, et al. (2010). Modulation of the response to a somatosensory stimulation of the hand during the observation of manual actions. Experimental Brain Research. 208: 11-19.
40. Post LJ, Zompa IC, Chapman CE. (1994). Perception of vibrotactile stimuli during voluntary motor activity in human subjects. Experimental Brain Research. 100: 107-120.
41. Johansson RS, Vallbo AB. (1979). Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. Journal of physiology. 286: 383-300.
42. Starr A, Cohen LG. (1985). Gating of somatosensory evoked potentials begins before the onset of voluntary movement in man. Brain Research. 348: 183-186.

APPENDIX A

Table A1: Subject 1, 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).

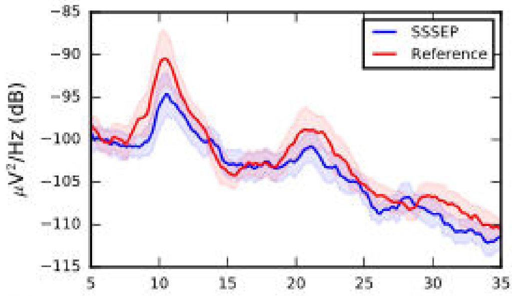
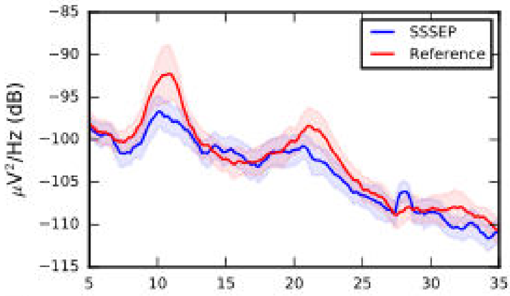
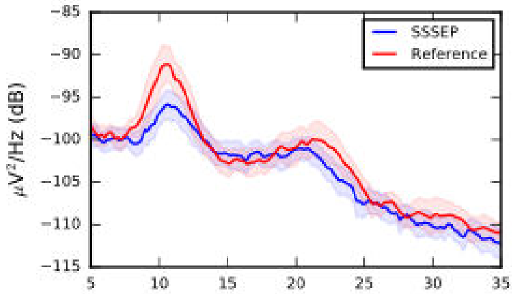
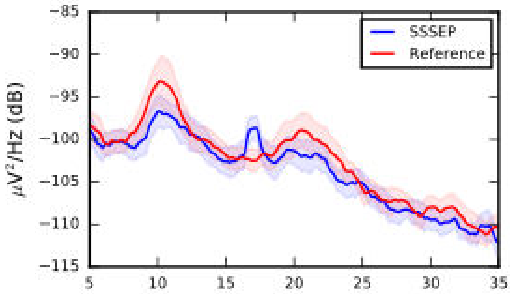
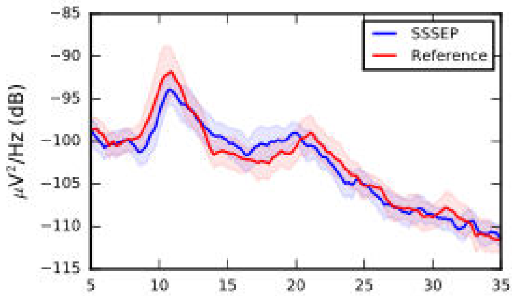
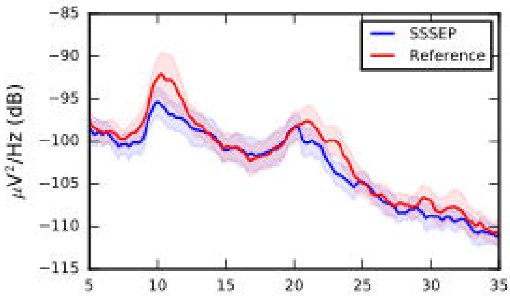
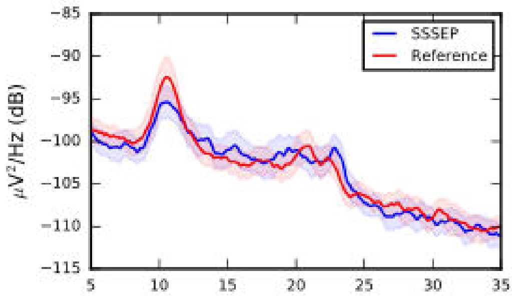
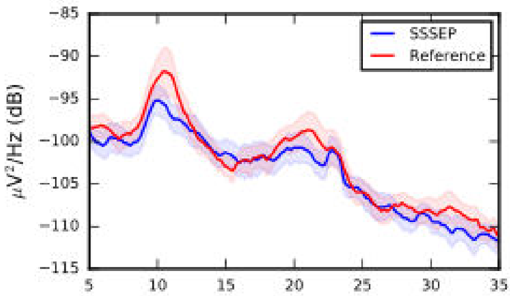
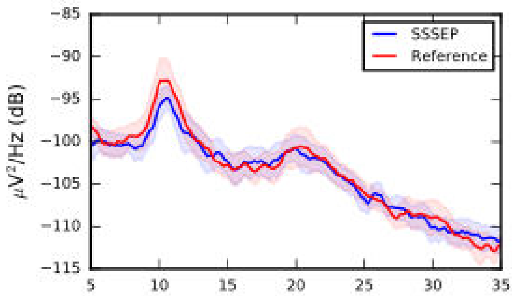
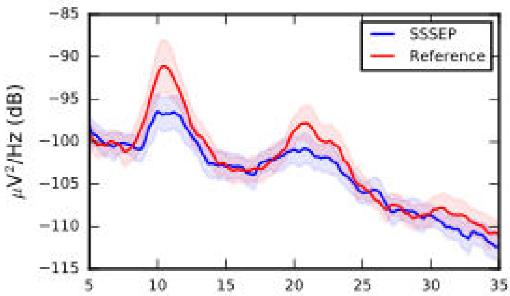
Frequncy (Hz)	Left index finger	Right index finger
14		
17		
20		
23		
26		

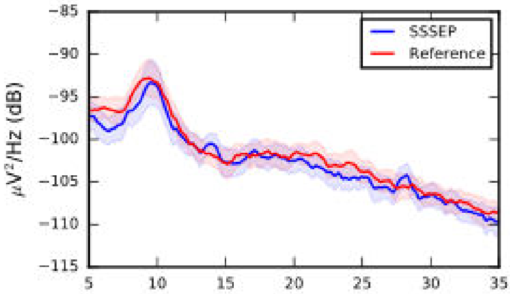
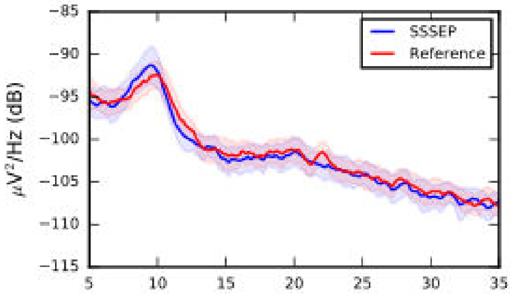
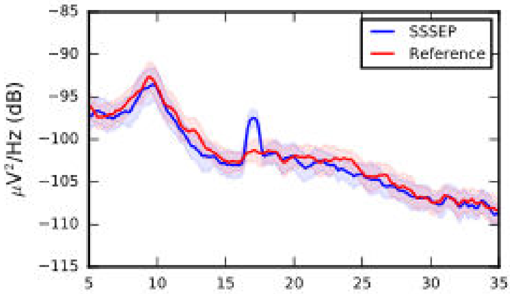
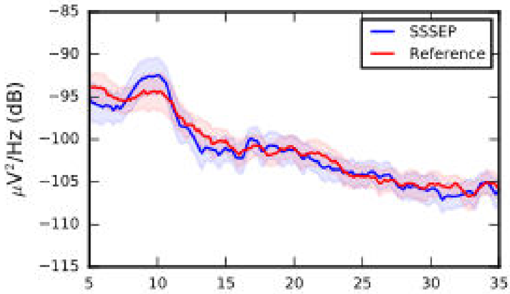
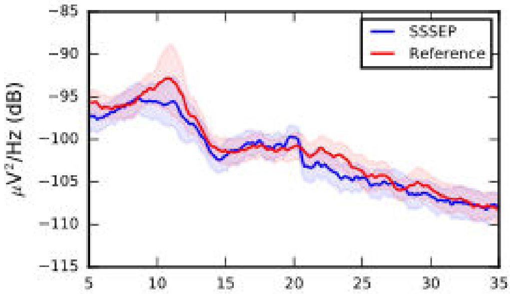
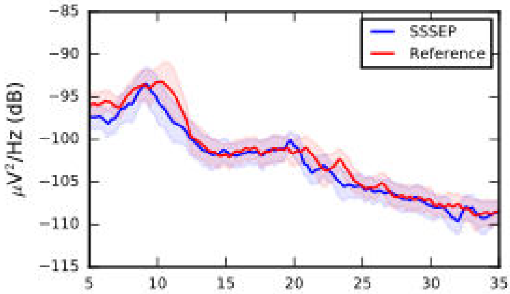
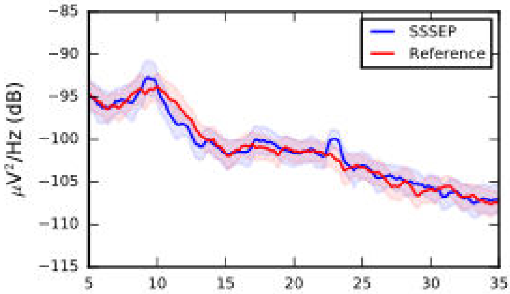
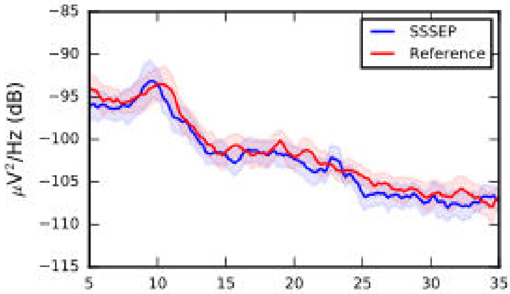
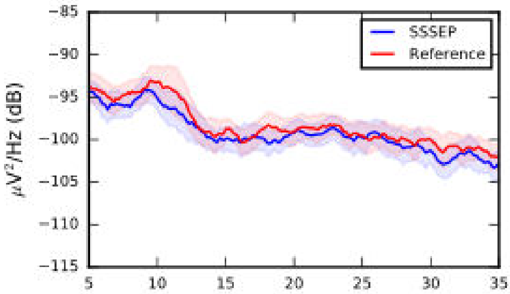
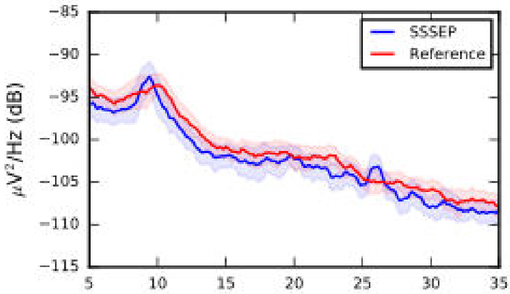
Table A2: Subject 2, SSSEP (blue) and reference signal (red), for left index finger (left column) and right index finger (right column), at the frequencies: 14, 17, 20, 23 and 26 Hz (from top to bottom).		
Frequncy (Hz)	**Left index finger**	**Right index finger**
14		
17		
20		
23		
26		

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).

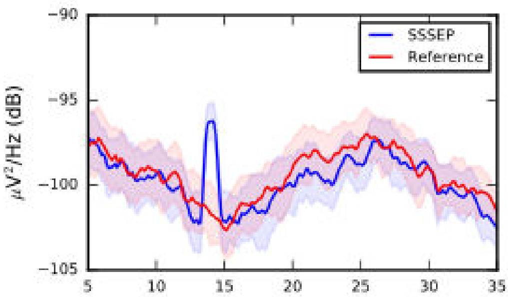
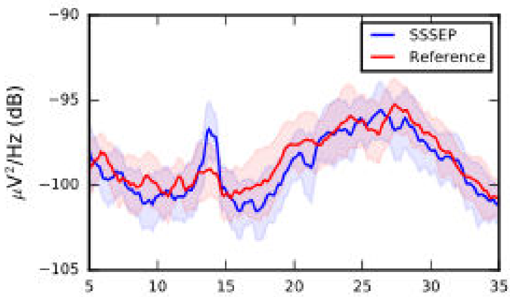
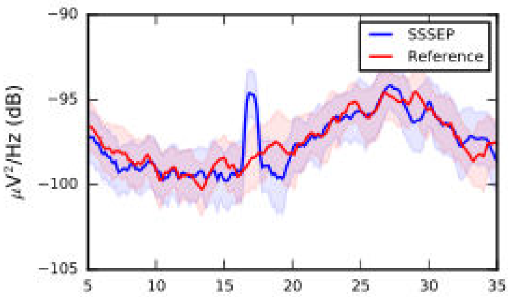
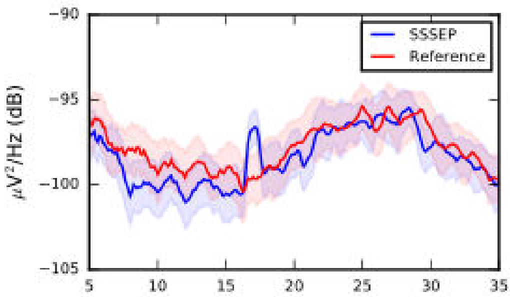
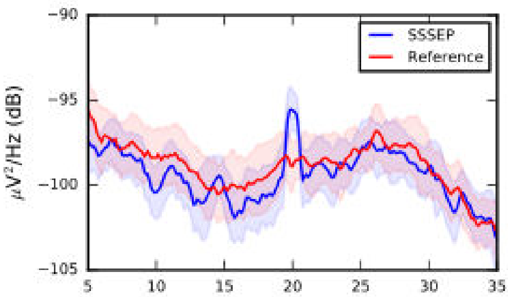
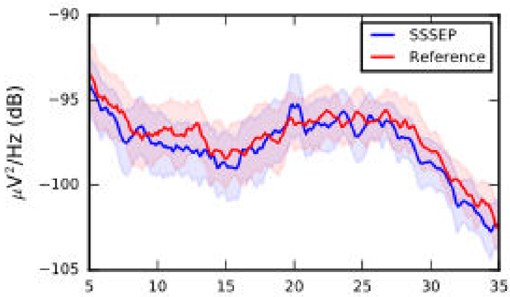
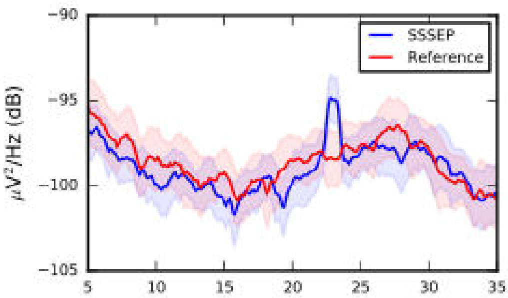
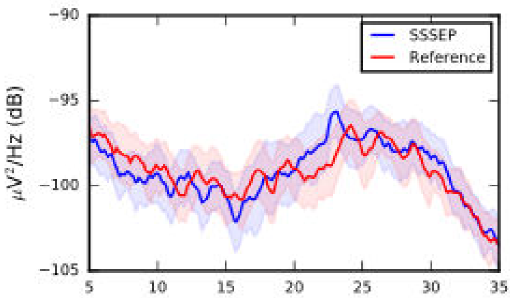
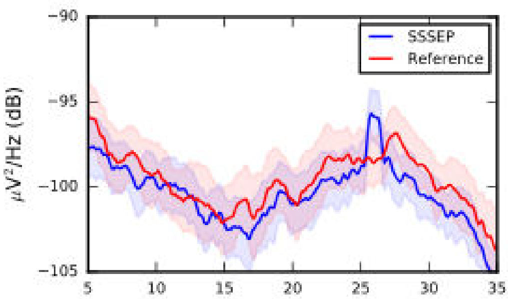
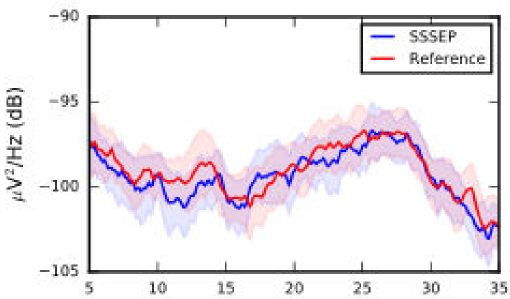
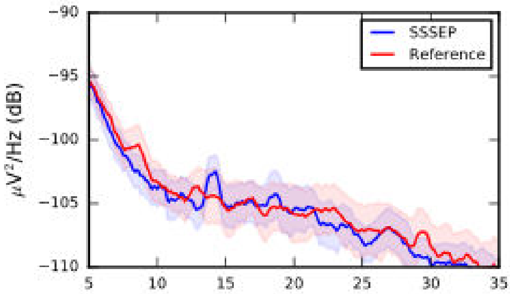
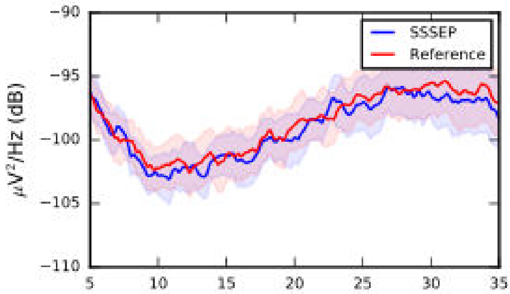
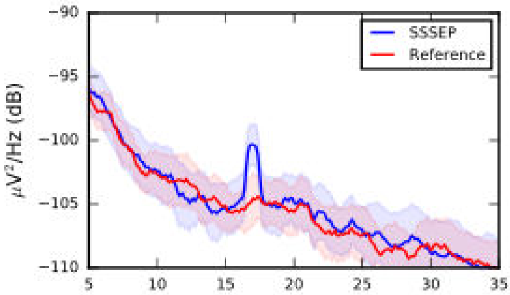
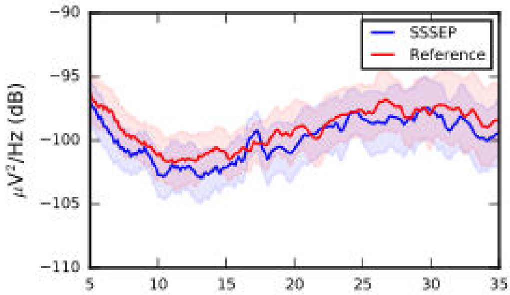
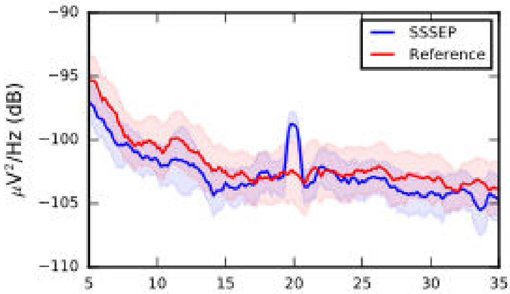
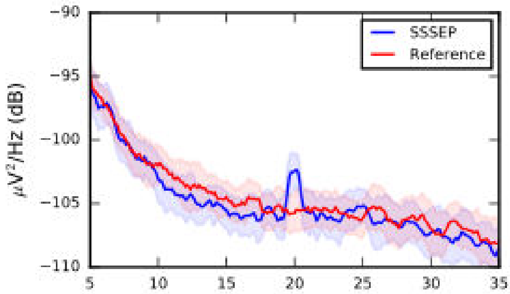
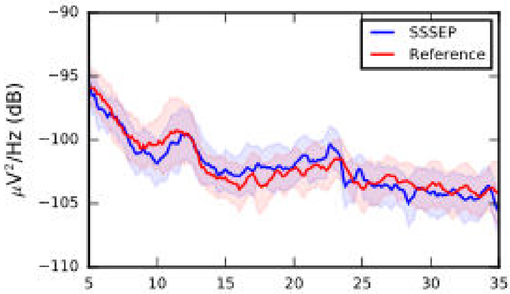
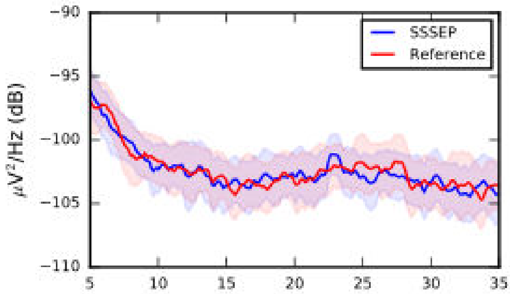
Frequncy (Hz)	Left index finger	Right index finger
14		
17		
20		
23		
26		

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).

Frequncy (Hz)	Left index finger	Right index finger
14		
17		
20		
23		
26