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Published in:
IEEE Transactions on Neural Systems and Rehabilitation Engineering

DOI (link to publication from Publisher):
10.1109/TNSRE.2017.2684084

Publication date:
2017

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Yao, L., Sheng, X., Zhang, D., Jiang, N., Mrachacz-Kersting, N., Zhu, X., & Farina, D. (2017). A stimulus-independent hybrid BCI based on motor imagery and somatosensory attentional orientation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *25*(9), 1674-1682. Article 7880549. https://doi.org/10.1109/TNSRE.2017.2684084

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TNSRE.2016.2572226, IEEE Transactions on Neural Systems and Rehabilitation Engineering

A BCI System based on Somatosensory Attentional Orientation

Lin Yao, Xinjun Sheng, Dingguo Zhang, Ning Jiang, Dario Farina, Xiangyang Zhu*

***Abstract*— We propose and test a novel brain-computer interface (BCI) based on imagined tactile sensation. During an imagined tactile sensation, referred to as somatosensory attentional orientation (SAO), the subject shifts and maintains somatosensory attention on a body part, e.g., left or right hand. The SAO can be detected from EEG recordings for establishing a communication channel. To test for the hypothesis that SAO on different body parts can be discriminated from EEG, 14 subjects were assigned to a group who received an actual sensory stimulation (STE-Group), and 18 subjects were assigned to the SAO only group (SAO-Group). In single trials, the STE-Group received tactile stimulation first (both wrists simultaneously stimulated), and then maintained the attention on the selected body part (without stimulation). The same group also performed the SAO task first and then received the tactile stimulation. Conversely, the SAO-Group performed SAO without any stimulation, neither before nor after the SAO. In both the STE-Group and SAO-Group, it was possible to identify the SAO-related oscillatory activation that corresponded to a contralateral event-related desynchronization (ERD) stronger than the ipsilateral ERD. Discriminative information, represented as R^2, was found mainly on the somatosensory area of the cortex. In the STE-Group, the average classification accuracy of SAO was 83.6%, and it was comparable with tactile BCI based on selective sensation (paired-t test, $P > 0.05$). In the SAO-Group the average online performance was 75.7%. For this group, after frequency band selection the offline performance reached 82.5% on average, with ≥80% for 12 subjects and ≥95% for 4 subjects. Complementary to tactile sensation, the SAO does not require sensory stimulation, with the advantage of being completely independent from the stimulus.**

***Index Terms*— Brain Computer Interface (BCI), Selective Sensation (SS), Somatosensory Attentional Orientation (SAO), Imagined Sensation.**

I. INTRODUCTION

Brain-computer Interface (BCI) permits direct interaction between the human brain and the external environment, allowing brain actuated communication and control. This technology may be particularly useful for locked-in patients without any peripheral afferent nerve and muscle functions [1]. Due to sensory and motor impairments, independent BCIs without requirement of external stimulation, such as auditory, visual or tactile, have attracted extensive interest [2]–[4]. Among these, motor imagery (MI) based BCI is the most common solution investigated. It has been indeed demonstrated that subjects can voluntarily modulate sensorimotor rhythms (SMR) generated mainly from the motor cortex, by performing imagined movement of their limbs (e.g., left or right hand). The brain signals induced by MI enable direct BCI control by subjective motor intention [5]. In addition to establishing a communication channel, performing the MI tasks could also have a rehabilitation benefit by promoting cortical plasticity [6]. Complementary tasks to MI may also be considered a source of BCI control. These other mental tasks would largely extend the framework of independent BCI and diversify the BCI applications.

Besides mental task of motor imagery, cognitive task of attention [7], [8], has also been utilized for BCI design. The processing of sensory stimuli is accompanied by attention, thus the subjective attentional intention may be decoded from stimulus evoked potentials. It has been shown that brain response evoked (transient and steady-state potential) or induced (oscillatory power) by exogenous stimulus can help the voluntary attention decoding, resulting in at least three BCI categories: (1) transient BCI, (2) steady-state BCI, and (3) oscillatory BCI. In transient BCI, transient auditory, visual or somatosensory stimuli are required. This class of BCI includes the visual P300 based speller [9], auditory and tactile ERP based target selection [10], [11]. In steady-state BCI, sustained auditory, visual or somatosensory stimuli are used. This class is represented by auditory steady-state evoked potentials (ASSEP) [12], steady-state visual evoked potentials (SSVEP) [13], and steady-state somatosensory evoked potential (SSSEP) [14]–[16]. In addition to evoked potentials and steady-state responses, sensory stimulation can also induce oscillatory rhythmic activities [17], which may reflect the way in which the brain processes these stimuli [18], [19]. This is the main characteristics of oscillatory BCIs. For example, we recently proposed a selective sensation based BCI [20], [21], in which tactile sensation is required to selectively modulate the oscillatory rhythmic power induced by tactile stimulus to the wrist. In this example, attentional intention can be reliably detected to enable a direct brain-computer interaction.

Psychologically, attention is also an endogenous top-down mental activity. Even when the external sensory stimulation is not actually delivered, there is a selective activation of corresponding brain substrates for the direction of attention to the

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sensation. This mechanism may allow the decoding of covert attention from attention-generated spontaneous rhythms. This preparatory neural activity before the appearance of a sensory stimulus, has been explored during visuospatial attention [22], [23], as well as during somatosensory attention [24]–[26]. In covert visuospatial attention (CVSA), i.e. the focus of attention on different regions of the visual field without overt eye movements, it has been observed that selective activation of the parieto-occipital α oscillation reflects endogenous shifts in the locus of visual attention [27]. Moreover the endogenous brain activation from the CVSA task has been shown to allow construction of an independent BCI without visual stimulation and especially without overt eye movement [28], [29]. Therefore, it is possible that covert visual attention is decoded even without the presence of the visual stimulus. Similar to the discrimination of EEG oscillations when performing real or only imagined movements, in this study, we focused on imagined sensation, also referred to as somatosensory attentional orientation, SAO. In this task, the subjects shift and maintain the somatosensory attention on a body part, with or without the actual somatosensory stimulus. It was hypothesized [24] that the SAO task would selectively activate the neural substrates of the somatosensory cortical resources, with a potential for a novel stimulus-independent BCI paradigm.

Motivated from the tactile BCI based on oscillatory activation of the somatosensory cortex (induced by mechanical vibrotactile stimulation on the wrist) [20], we designed experiments that prove the transition between BCI systems that need the actual tactile sensation to a paradigm that only involved imagined sensation. Therefore, we focused on whether brain signals (mainly from the somatosensory cortex) induced by SAO could be reliably recognized, and used for an independent BCI modality without the requirement of tactile stimulation.

II. Methods

A. Subjects

Twenty-five healthy subjects participated in the experiments (four females, all right handed, average age of 23.1 ± 1.3 years). Four of them had previously participated to a BCI study on selective sensation, whereas the others were naive subjects. The subjects were randomly assigned to two groups. Fourteen subjects were part of the control group that received the stimulation (STE-Group) and 18 subjects were part of the somatosensory attentional orientation only group (SAO-Group). To investigate the reliability of SAO for BCI use, seven subjects participated to both group studies. The study was approved by the Ethics Committee of Shanghai Jiao Tong University, China. All participants signed informed consent forms before participation.

B. EEG Recording and Somatosensory Stimulation

EEG signals were recorded using a SynAmps2 system (Neuroscan, U.S.A.). A 64-channel quick-cap was used to collect 62-channel EEG signals, and the electrodes were placed according to the extended 10/20 system. The reference electrode was located on the vertex, and the ground electrode was located on the forehead. An analog filter with bandwidth 0.5-70Hz and a notch filter at 50Hz were applied to the raw signals. The signals were digitally sampled at 250Hz. The common average reference (CAR) spatial filter was used for the off-line analysis. Additionally, two bipolar electrodes were also attached to the flexor carpi radialis muscle of the left and right hand, and were acquired with the EEG signals using the same acquisition system.

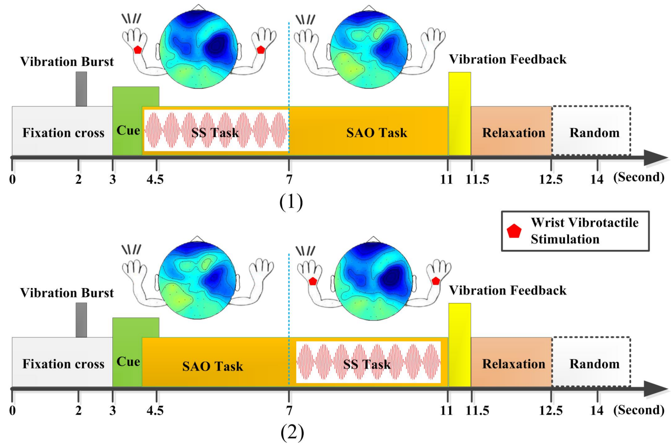

Fig. 1. Graphic representation of the experimental paradigm in STE-Group. (A) Translation block, in which subjects performed a selective sensation task first (both wrists were simultaneously stimulated), and followed by the somatosensory attentional orientation task (no somatosensory vibration stimulation). (B) Evaluation block, in which subjects performed a somatosensory attentional orientation task first (no somatosensory vibration stimulation), and followed by the selective sensation task (both wrists were simultaneously stimulated). The axis is in second.

Mechanical stimulation was applied to the wrist. The stimulation device produced a 23-Hz sine wave for the left wrist, and 27-Hz sine wave for the right wrist, Both stimulations were modulated with a 175-Hz sine carrier wave. In this study, two types of mechanical receptors, Pacinian corpuscles and Meissner corpuscles, were stimulated. These receptors are sensitive to frequencies above 100Hz and 20-50Hz, respectively [16]. Linear resonant actuators (10 mm, C10-100, Precision Microdrives Ltd., typical normalized amplitude 1.4 G) were used for vibrotactile stimulation. The amplitude of the vibration was individually adjusted within the range of 0.5 times the maximum amplitude to the maximum amplitude (11.3 μm) at the resonant frequency. The selection of the optimal amplitude was based on the feedback of the subject, such that subjects could comfortably feel the vibration.

C. Experimental Paradigm for the STE-Group

Each subject performed a translation block and an evaluation block, and took adequate rest between them (5 to 20 minutes). In the translation block, the subjects were required to perform a selective sensation task according to the given cue, and then maintain the attention on the selected body part (SAO task) while the vibration stimuli were off. In the evaluation block, the subjects were required to shift and focus their somatosensory attention to the corresponding body part according to the given cue (without somatosensory stimulation), and then perform the selective sensation while the stimuli were delivered.

1) Translation Block Paradigm: The experimental paradigm is illustrated in Fig. 1 (A). Each subject seated on a comfortable armchair in an electrically shielded room. With both forearms and hands resting on the armrest, the subject limited as much as possible the eye blinking and the facial or arm muscular activations. Within each trial, the subject performed left or right selective sensation according to the cue (during task time, the left and right wrists were simultaneously stimulated), while maintaining the attention on the selected hand when the vibration stimuli were turned off. A total of 120 trials (60 left and 60 right classes) were performed by the subjects in 3 runs, with 1-2 min between runs. At the beginning of each trial, a fixation symbol ("+") appeared in the center of the screen. After 2s, a vibration burst with the same intensity stimulated both hands to alert the user of the subsequent task. The vibration pulse lasted 200 ms. Then at the 3rd second, a red cue pointing either left (L-SS) or right (R-SS) was presented on the computer monitor. This cue was superimposed to the fixation symbol and lasted for 1.5s. The subjects were instructed to perform the mental task after the appearance of the cue arrow. The mental task continued for 8s, until the fixation symbol disappeared. For half of the mental task, the vibrotactile stimulation was simultaneously applied to both wrists whereas for the remaining half of the task there was no stimulation. During the first run, there was no feedback after the L-SAO and R-SAO tasks. During the subsequent two runs, a vibration feedback was provided to the subject after the SAO task. The feedback stimulus was applied according to the decoded task (left or right wrist) and lasted for 500ms. The on-line classifier was calibrated using the EEG data during the L-SAO and R-SAO task period, and used to classify the subsequent SAO task (see the description of the algorithm below). Next there was a relaxation time period lasting 1.5s. Finally a random time interval of 0 to 2s followed the resting time, to avoid subjects adaptation.

2) Evaluation Block Paradigm: The experimental paradigm is illustrated in Fig. 1 (B). For each trial, the subjects performed SAO task first according to a given cue (without sensory stimulation), and then during stimulation. A total of 120 trials were performed by the subjects in 3 runs. The timing of the trials was the same but the vibrotactile stimulation was applied in the second half of the mental task. The on-line classifier was also calibrated using the EEG data during the L-SAO and R-SAO task period and on-line adapted, and used to classify the subsequent SAO task.

D. Experimental Paradigm for the SAO-Group

While in the same position as the STE-Group, within a trial, the subject's task was to perform left or right SAO task according to a cue, without any tactile stimulation. A total of 200 trials were performed by the subjects in 5 runs, with 1-2 min rest between runs. At the beginning of each trial, a fixation symbol ("+") appeared in the center of the screen. Then, a vibration burst with the same intensity stimulated both hands for 200 ms. This was followed by a red cue pointing either left (L-SAO) or right (R-SAO) on the computer monitor. This cue was superimposed on the fixation symbol for 1.5s. The subjects were instructed to perform the mental task after the appearance of the cue. The mental task continued until the fixation symbol disappeared. During the first run, there was no feedback after the SAO tasks. During subsequent four runs, there would be vibration feedback after the SAO task. The feedback stimulus was applied according to the decoded task type (left or right) for 500ms. A resting period of 1.5s and a random interval of 0 to 2s followed.

E. Calculation of ERD/ERS and Time Frequency Decomposition

Event related desynchronization (ERD) or event related synchronization (ERS) are defined as the percentage of power decrease (ERD) or power increase (ERS) in a defined frequency band in relation to a reference interval (baseline) [30]. The frequency band alpha-beta of [8 26] Hz was adopted in this study for EEG filtering before the ERD/ERS calculation. The reference interval for the ERD/ERS calculation was -2.0s to -1.2s prior to the appearance of the cue. The grand averaged ERD/ERS curves were used to determine the activation and deactivation of the brain areas involved in the mental tasks.

The EEG data were manually corrected for artifact using EEGLAB toolbox [31]. The trials contaminated with swallowing and physical movement artifact et al (either in baseline or taskline interval), were excluded for the analysis, and for every subject more than 45 trials (every class) were used for subsequent analysis (while no trials were discarded for the classification evaluation). Time-frequency decomposition of each trial along each EEG channel was undertaken to construct the spatio-spectral-temporal structure according to the predefined mental tasks. It was calculated every 200 msec with a hanning tapper, convoluted with a modified sinusoid basis in which the number of cycles linearly changed with frequency to achieve proper time and frequency resolution [32]. The R^2 index [21], [33], [34] was calculated based on the above spatio-spectral-temporal structures between different mental tasks, and used to locate the component of different EEG channels for the classification of the two corresponding mental tasks. The Discriminative Brain Pattern (DBP) was defined as a topographic plot of the R^2 index, which was averaged along the task-line time interval mentioned above, and along certain frequency bands, such as alpha of [8 13] Hz, beta of [13 26] Hz, or alpha-beta of [8 26] Hz. Besides R^2 maps, event-related spectrum perturbation (ERSP) at the critical channels of C3 and C4 was also analyzed to further have a comprehensive interpretation about the mental task process [35], and non-significant parts were wiped out under bootstrap significance level of P=0.01, using eeglab [31].

F. Algorithms and Performance Evaluation

Spatial filtering technique was adopted for both reducing the number of channels and for enhancing the feature discrimination between different mental tasks. The spatial filters were determined with the Common Spatial Pattern (CSP) procedure, which has been extensively validated for BCI

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[36], [37]. The log variance of the first three and last three components of the spatially filtered signals were chosen as feature vectors, and linear discriminative analysis (LDA) was used for classification. During the on-line experiment, spatial filters and LDA parameters were retrained at every trial, i.e., the classification of the current trial was based on 40 trials in the previous run and trials before the current trial in the same run [20].

As the most discriminative frequency bands are highly subject-dependent, the bands were selected as: lower alpha [8 10] Hz ($\alpha-$), upper alpha [10 13] Hz ($\alpha+$), lower beta [13 20] Hz ($\beta-$), upper beta [20 26] Hz ($\beta+$), alpha [8 13] Hz (α), beta [13 26] Hz (β), alpha-beta [8 26] Hz ($\alpha\beta$), and [10 16] Hz (η, good for some subjects to our experience). A fourth-order Butterworth filter was applied to the raw EEG signals before the CSP spatial filtering. A 10×10 fold cross-validation was utilized to evaluate the BCI performance among different frequency bands, and for selecting the sub-optimal frequency band.

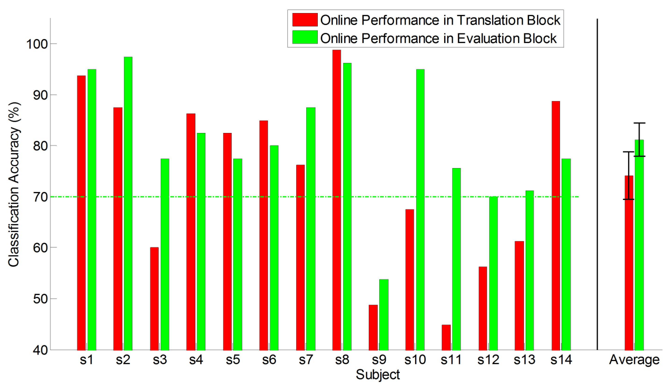

Fig. 2. Online BCI performance of SAO in the translation and evaluation block. Red bars indicate the discrimination accuracy between left and right SAO tasks in translation block. Green bars indicate the discrimination accuracy between left and right SAO tasks in evaluation block. The green dash-dotted line indicates 70% accuracy. Note that the first seven subjects also participated SAO-Group study.

EEG signals with respect to selective sensation and SAO in the STE-Group were extracted for performance evaluation. In the translation block, 1 to 4 seconds after the appearance of the cue were extracted for left and right SS task discrimination (the timing interval of the 4th to 7th seconds from the beginning of the trial), and 5 to 8 seconds after the appearance of the cue were extracted for left and right SAO task discrimination. The same was done for the evaluation block. In the SAO-Group, 1 to 4 seconds after the appearance of indicating cue were extracted for left and right SAO task discrimination.

III. Results

A. *SAO based Independent BCI Performance in Stimulation-involved STE-Group*

Fig. 2 shows the online BCI performance of SAO in the translation and evaluation blocks (classification between left-SAO and right-SAO). The averaged classification accuracy was 74.1% and 81.2% respectively. Table I demonstrates the offline performance of both SS and SAO tasks in the translation and evaluation blocks. After the frequency band selection, the averaged group level performance of SAO reached 80.5% in the translation block and 86.7% in the evaluation block. Furthermore, the classification of SAO had similar performance as SS (paired-t test, $P > 0.05$, in both evaluation and translation block), where the tactile stimulation was delivered.

To better understand the eletrophysiological characteristics of the SS (tactile sensation) and SAO (imagined sensation), the time-varying grand-averaged ERD/ERS at small-Laplace filtered C3 and C4 channels (within alpha-beta frequency band [8 26]Hz), are shown in Fig. 3. In both translation and evaluation blocks, the contralateral activation was stronger as compared to the ipsilateral activation, i.e. during the left selective sensation task the ERD of the contralateral right hemisphere (channel C4) was congruently stronger than that of the ipsilateral left hemisphere (channel C3), and vice versa for the right selective sensation. Similarly, the SAO tasks also showed a stronger contralateral activation as compared to the ipsilateral activation. Specifically, when performing the attentional task (selective sensation or SAO), the external somatosensory vibration stimulation induced a stronger ERD activation (Fig. 3 (B)) after approximately 4s of vibration. The ERSP of a representative subject are shown in Fig. 6 (translation block) and Fig. 7 (evaluation block). It can be observed that the tactile stimulation induced a stable oscillatory activation in both the alpha and beta frequency bands, with a stronger contralateral activation. The SAO task was also characterized by contralaterality and by a weaker ERD with respect to the tactile sensation, as expected.

The discriminative information distribution, represented as R^2, is shown in Fig. 4 (naive subject) and Fig. 5. There was a high similarity in EEG activation with the tactile sensation and the SAO tasks, with the main discriminative information in the somatosensory area.

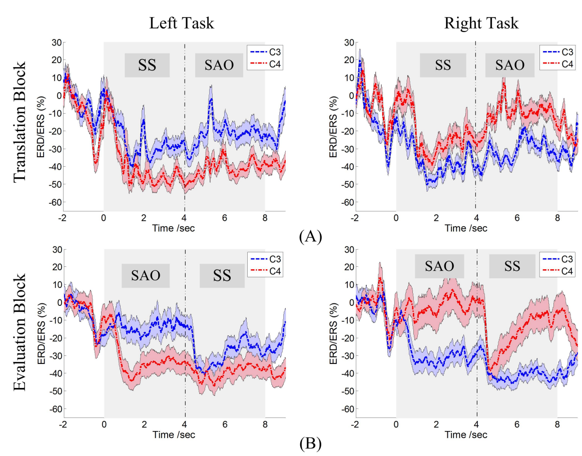

Fig. 3. The time varying grand-averaged ERD/ERS curves at small-laplace filtered C3 and C4 channels within alpha-beta frequency band [8 26] Hz. (A) ERD/ERS corresponds to left and right tasks in the translation block. (B) ERD/ERS corresponds to left and right tasks in the evaluation block. The upper and lower curves indicate standard error. Time 0s corresponds to the time when the indicating cue appeared (3rd second from the beginning of the trial). Time 4s corresponded to time point of the tasks alternation.

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TABLE I

CLASSIFICATION ACCURACY FOR SS AND SAO TASKS IN THE TRANSLATION AND EVALUATION BLOCKS.

Subject	Translation Block(%)				Evaluation Block(%)			
	SS	SS (+)	SAO	SAO (+)	SAO	SAO (+)	SS	SS (+)
s1	98.6±0.6	98.8±0.9 (β+)	92.3±0.8	96.1±1.2 (α+)	99.8±0.4	99.8±0.4 ($\alpha\beta$)	87.3±2.0	90.0±1.6 (α+)
s2	71.4±2.2	87.8±1.7 (β+)	72.8±3.4	85.2±2.8 (β+)	97.7±0.9	98.9±0.7 (α+)	91.7±1.5	91.7±1.5 ($\alpha\beta$)
s3	77.6±1.8	77.8±2.1 (η)	61.3±1.1	69.0±2.0 (η)	91.0±1.4	91.0±1.4 ($\alpha\beta$)	73.1±1.2	80.6±1.3 (α+)
s4	75.3±1.4	84.4±1.7 (β)	91.9±1.1	94.1±1.1 (η)	88.7±1.3	94.1±1.1 (η)	88.4±2.1	95.3±1.0 (η)
s5	87.3±1.7	87.3±1.7 ($\alpha\beta$)	79.4±2.0	79.5±2.1 (α)	75.8±2.2	82.8±2.1 (η)	82.2±1.9	92.8±1.4 (α+)
s6	84.8±1.4	84.8±1.4 ($\alpha\beta$)	78.2±2.2	79.4±1.5 (α)	81.5±2.2	82.3±1.6 (η)	96.1±0.8	96.1±0.8 ($\alpha\beta$)
s7	75.2±1.7	75.2±1.7 ($\alpha\beta$)	78.5±2.7	93.9±0.8 (η)	90.7±1.5	94.8±1.0 (η)	81.8±1.9	82.6±1.9 (η)
s8	94.2±1.4	95.8±1.5 (β)	98.8±0.6	98.8±0.6 ($\alpha\beta$)	98.2±0.5	98.3±1.0 (η)	96.5±1.1	97.1±0.6 (η)
s9	58.3±3.1	66.3±2.7 (η)	56.0±2.3	67.7±2.9 (α)	58.8±2.7	67.2±2.7 (α+)	56.6±3.6	69.3±3.7 (α+)
s10	65.9±2.7	72.5±2.5 (β)	69.1±2.9	72.4±3.7 ($\beta-$)	93.7±1.1	95.3±1.1 (η)	84.8±2.4	92.3±1.4 (β)
s11	71.8±3.1	71.8±3.1 ($\alpha\beta$)	51.4±3.6	59.5±3.5 (β+)	73.1±2.4	73.1±2.4 ($\alpha\beta$)	76.2±1.9	76.2±1.9 ($\alpha\beta$)
s12	58.4±1.7	65.7±2.3 (α+)	69.6±2.7	74.0±1.9 (η)	70.3±2.5	84.3±2.7 (α+)	77.5±2.0	88.7±1.7 (α+)
s13	62.6±2.9	74.0±2.4 (α)	61.6±3.4	68.5±2.1 (α)	65.3±3.1	72.5±3.0 (α)	67.2±2.4	77.8±2.6 (α)
s14	77.3±0.9	82.3±2.1 (α)	88.7±1.4	89.6±1.7 (α)	78.7±2.1	79.6±1.0 (α+)	69.6±3.1	71.8±2.1 (η)
Mean	75.6±12.4	80.3±10.2	75.0±14.5	80.5±12.5	83.1±13.1	86.7±10.8	80.6±11.5	85.9±9.4

Note: the first seven bold highlighted subjects also participated SAO-Group study.

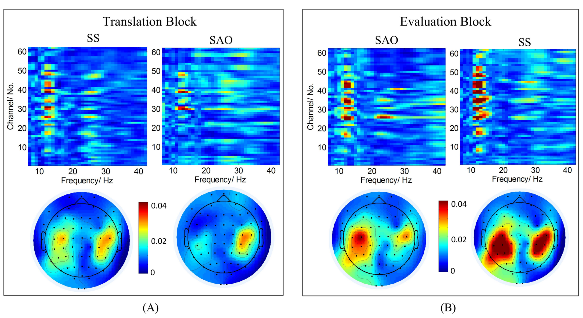

Fig. 4. R^2 value distribution from a representative naive subject (s5). (A) Corresponded to the translation block, with upper row represented R^2 value distribution across frequency and spatial domains in selective sensation and SAO, lower row represented the discriminative brain pattern (DBP) averaged along the upper alpha [10 13] Hz frequency range, the color bar indicated the R^2 value. (B) Corresponded to the evaluation block.

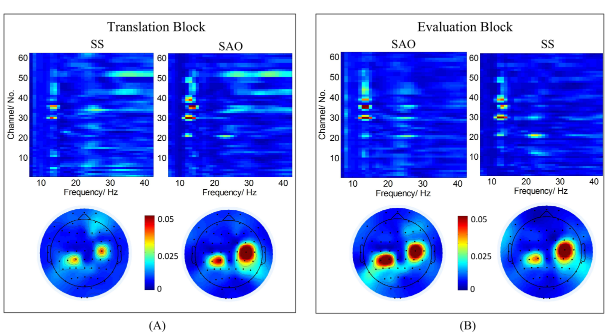

Fig. 5. R^2 value distribution from a representative subject experienced in selective sensation (s8). (A) Corresponded to the translation block, with upper row represented R^2 value distribution across frequency and spatial domains in selective sensation and SAO, lower row represented the discriminative brain pattern (DBP) at 13 Hz frequency, the color bar indicated the R^2 value. (B) Corresponded to the evaluation block.

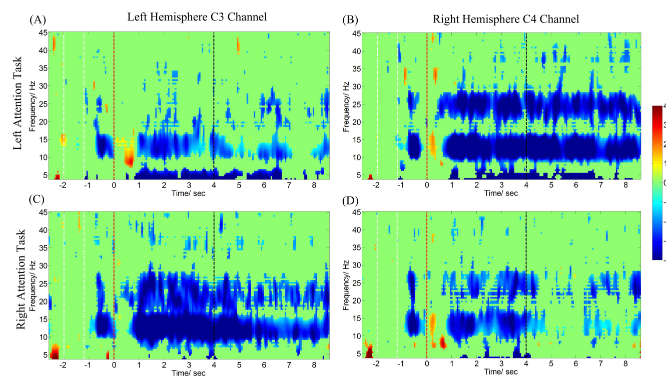

Fig. 6. Event related spectrum perturbation (ERSP) at the small-laplace filtered C3 and C4 channels in Translation Block (s5). (A) ERSP at left hemisphere C3 channel during the left attention task. The interval between white dash-doted line refers to the baseline ([-2 -1.2]s). The red dashed line refers to the appearance of the cue, and the black dashed line refers to the time when the vibration stimulus were off. (B) ERSP at right hemisphere C4 channel during the left attention task. (C) ERSP at left hemisphere C3 channel during the right attention task. (D) ERSP at right hemisphere C4 channel during the right attention task.

B. SAO based Independent BCI Performance in SAO-Group out of Sustained Tactile Stimulation

Fig. 8 illustrates both the online and offline BCI performance of SAO for the SAO-Group out of sustained tactile stimulation. The online classification accuracy was 75.7% while offline it reached 82.5% after frequency band selection. Fifteen subjects had accuracy above 70% (critical value for BCI-illiteracy problem [38], [39]), 12 above 80% and 4 above 95%.

The time-varying grand-averaged ERD/ERS for small-Laplace filtered C3 and C4 channels (within alpha-beta frequency band [8 26]Hz), are also shown in Fig. 9. This figure shows that without the tactile stimulation, the brain activation corresponding solely to the SAO tasks presents contralateral activation. During the left-SAO task period, the ERD of the

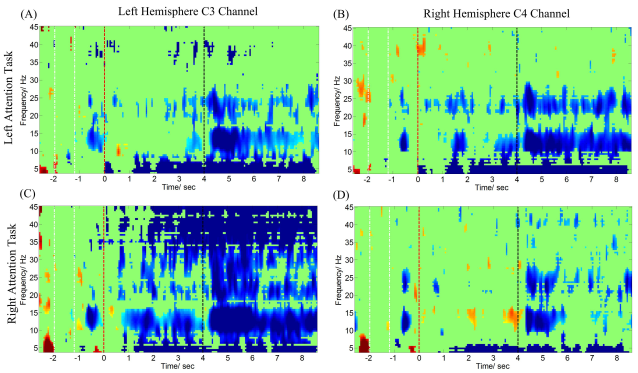

Fig. 7. Event related spectrum perturbation (ERSP) at the small-laplace filtered C3 and C4 channels in Evaluation Block (s5). (A) ERSP at left hemisphere C3 channel during the left attention task. The interval between white dash-doted line refers to the baseline ([-2 -1.2]s). The red dashed line refers to the appearance of the cue, and the black dashed line refers to the time when the vibration stimulus were on. (B) ERSP at right hemisphere C4 channel during the left attention task. (C) ERSP at left hemisphere C3 channel during the right attention task. (D) ERSP at right hemisphere C4 channel during the right attention task.

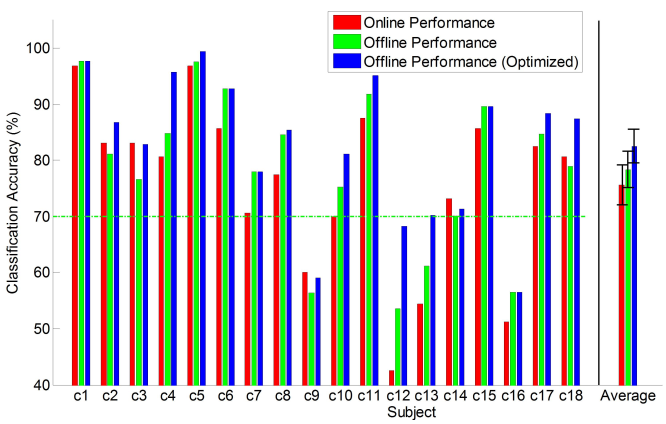

Fig. 8. BCI performance of SAO in SAO-Group out of sustained tactile stimulation. Red bars indicate the online BCI performance of SAO. Green bars indicate the offline BCI performance between left and right SAO tasks. Blue bars indicate the offline BCI performance after sub-optimal frequency band selection. The green dash-dotted line indicates 70% accuracy. Note that the first seven subjects also participated the STE-Group study.

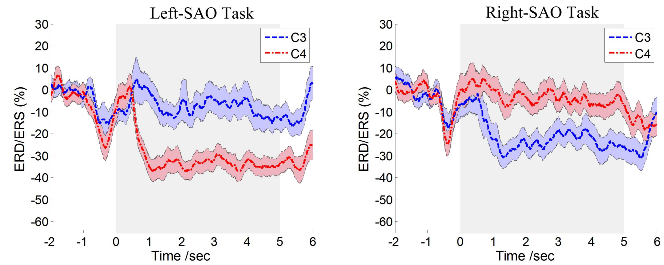

Fig. 9. The time varying grand-averaged ERD/ERS curves at small-laplace filtered C3 and C4 channels within alpha-beta frequency band [8 26] Hz in SAO-Group. ERD/ERS corresponds to left-SAO and right-SAO task. The upper and lower curves indicate standard error. Time 0s corresponds to the time when the indicating cue appeared (3rd second from the beginning of the trial).

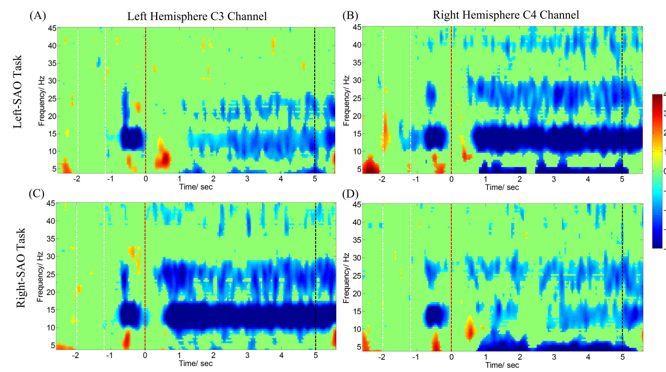

Fig. 10. Event related spectrum perturbation (ERSP) at the small-laplace filtered C3 and C4 channels in SAO-Group (c5). (A) ERSP at left hemisphere C3 channel during the left-SAO task. The interval between white dash-doted line refers to the baseline ([-2 -1.2]s). The red dashed line refers to the appearance of the cue, and the black dashed line refers to the time when subjects stop the task. (B) ERSP at right hemisphere C4 channel during the left-SAO task. (C) ERSP at left hemisphere C3 channel during the right-SAO task. (D) ERSP at right hemisphere C4 channel during the right-SAO task.

right hemisphere (C4 channel) was stronger than that of the left hemisphere (C3 channel), and vice versa for the right-SAO task. Furthermore, the ERSP of the same subject (shown in Fig. 6 and 7, naive subject) is reported in Fig. 10, that show that the sustained oscillatory dynamic could be induced through the mental task of SAO .

IV. Discussion

A. Existence and Efficacy of SAO based Independent BCI

In this study, we presented a new independent BCI based on SAO (imagined sensation). To the best of our knowledge, this is the first time that this covert somatosensory attention-based BCI system has been proposed and validated. The translational block paradigm in the STE-Group revealed the existence of the imagined sensation when the tactile stimulation was turned off, with an online classification accuracy of 74.1%. Moreover, the accuracy increased to 80.5% after subjective suboptimal frequency band selection. In addition, the evaluation block paradigm in the STE-Group further validated the efficacy of the SAO based BCI system, with an average online accuracy of 81.2% and offline performance of 86.7%. Furthermore, the SAO based BCI in the STE-Group has shown a comparable performance with the tactile BCI based on selective sensation. In the stimulation-involved STE-Group, the presence of tactile stimulation, which were always preceded before or followed after the SAO, might have assisted the imagined sensation task to be possible. However, the discrimination ability with SAO was also tested without any stimulation in the SAO-Group and corresponded to an average accuracy of 75.7% online and 82.5% offline, with the majority of the subjects showing accuracy above 70%. Therefore, the proposed SAO BCI may be a good alternative to current BCI systems, especially when sensory pathways are impaired.

The central processing of sensory stimuli has been indeed used in several previous BCI paradigms, such as transient ERP potential based BCI [9]–[11], stead-state evoked potential based BCI [12]–[14], and induced oscillatory based tactile BCI [20], [21]. The visual P300 and SSVEP BCIs have demonstrated a greater information transfer rate compared with the other BCI modalities, with the disadvantage that an external visual stimulation and volitional gaze control are needed. These needs may limit the applicability in completely locked-in patients. Tactile BCI provides a complementary approach that increases BCI diversity by fully exploring the existing somatosensory system [40]. The first prototype of tactile BCI has been proposed by Mueller-Putz in 2006 [14] and was based on steady-state somatosensory evoked potentials (SSSEP). This system does not need the user to move the eyes, which is especially useful for locked-in patients without eye control. The classification accuracy for this BCI modality ranged from 64% to 84%, with average accuracy of 70.4%. Four of the investigated subjects resulted in accuracy below 70%, which is used to define the critical level for BCI illiteracy [38], [39]. Therefore, those data revealed 80% of BCI-illiteracy in the small tested population of 5 subjects. Later, a tactile P300 system, based on the oddball paradigm, has been proposed [11]. This system achieved a mean accuracy of approximately 72% in 11 subjects for two target selections. Further, we have proposed a tactile BCI based on oscillatory dynamics from the somatosensory area of the brain and we termed this approach as selective sensation BCI [20]. Up to now, 43 subjects have been recruited, with a mean accuracy of 79.2% and BCI-illiteracy rate of 16.3%. The present study followed our tactile BCI based on selective sensation and has shown that the majority of the subjects can achieve a classification accuracy $\geq$80%. This approach has the potential of making independent BCI more applicable.

This study has shown that without the presence of the sensory stimulation, the covert attention in somatosensory modality can be anyway decoded. Contrary to CVSA based BCI [27], [28], which enabled covert visual attention decoding without visual stimulation and especially without overt eye movement, in the somatosensory modality without physical tactile stimulation, the imagined sensation task has also induced oscillatory activation in the somatosensory area of the brain and enabled covert somatosensory attention decoding without any sensory input. Furthermore, during the SAO tasks, both in the STE-Group and SAO-Group, the contralateral ERD was stronger than the ipsilateral ERD, which is consistent with motor imagery studies (mentally simulated efferent output) [41] and tactile BCI based selective sensation (afferent input processing) [20]. The ERD dynamic induced by SAO, is well correlated with the activation of different brain regions and selective recruitment of corresponding brain substrates when attention is endogenously shifted and maintained by the brain even without the presence of external sensory stimulation.

B. Consideration on the Experimental Paradigm

Motivated by the motor imagery in BCI, our hypothesis was that also sensation could be imagined. The translation block in the STE-Group has been used to understand this passage from the tactile sensation to the imagined sensation. During the single-trial in the translation paradigm, the subjects performed tactile sensation first and, when the tactile was off, the subjects were required to maintain the somatosensory attention on the selected side. The evaluation block was subsequently carried out to directly evaluate the SAO performance. The SAO tasks might need the assistance of tactile stimulation and, also in order to keep the symmetry between the two blocks, the tactile sensation was also performed after the SAO task in the evaluation block. The translation block was carried out first in order to make the subjects experienced with the SAO task. Moreover the seven subjects who had shown a good performance during the STE-Group study, also participated the subsequent SAO-Group study in order to further validate this findings, and another eleven naive subjects were recruited for the evaluation.

In the STE-Group, the SAO tasks were always followed or preceded by tactile sensation, thus the imagined sensation might have been assisted by the presence of the sustained tactile stimulation during the single-trial task period. Therefore, to further evaluate the efficacy of the SAO task for BCI use, left and right SAO tasks without involvement of the sustained tactile stimulation were performed by the subjects in the SAO-Group.

This is a proof-of-the-concept study, thus we followed the cue-based paradigm and our previous experimental design [4], [21], [42]. According to that paradigm, at the beginning of each trial, there was a vibration burst lasting 200 ms, with the purposes of alerting the subject to be ready for the subsequent task. Furthermore, we recruited 4 more subjects to the SAO paradigm, in which we removed the vibration burst at the beginning of each trial and this did not negatively impact the performance. Transferring our current cue-based SAO paradigm study to the self-paced BCI applications will be our next objective.

C. Electrophysiological Association between Tactile Sensation and Imagined Sensation

Tactile stimulation has shown to evoke SSSEP component [14], which has a frequency specific feature; besides that, it has also shown to induced ERD/ERS oscillatory activation [20], which has a non-stimulation frequency specific feature, and can largely increase current tactile BCI performance. This stimulation induced ERD/ERS activation from the somatosensory cortex functions as the only bridge between the real sensation and imagined sensation.

It was clearly observed that the vibration burst to alert the subject to get ready for the subsequent task induced an oscillatory ERD response in the [8 26] Hz alpha and beta frequency bands in both the left and right hemisphere (Figs. 3, 6, 7, 9 and 10), but did not exhibit task-related differences because no specific tasks were performed. During the tactile stimulation in the translation block, the ERD oscillatory activation showed task-related differences in the left and right brain regions (C3 and C4 channels). The left tactile sensation task resulted in a stronger ERD in the contralateral right hemisphere than the ipsilateral left hemisphere, and vice versa. After the cessation of the tactile stimulation in the translation block, the same laterality was observed during the SAO tasks. The discriminative brain activity of the SS and SAO tasks in both translation and evaluation block are mainly focused on the somatosensory area of the brain (Figs. 4 and Fig. 5). During the somatosensory task (both selective sensation and SAO), the sensory stimulation showed increased cortical activation, as indicated by the stronger ERD strength when the vibrotactile stimulation was on (Fig. 3 (B)). The event-related rhythmic dynamics as revealed from the experimental paradigm lays the fundamental mechanism of the newly uncovered stimulus independent SAO task for the possible BCI use.

D. Comparison with MI and Potential Applications

Through mental simulation or imagination of the kinaesthetic movement of the subject's left or right hand, the brain signals generated mainly in the motor cortex can be used for BCI design. Because of the stimulus independent nature of the MI task, and relatively stable oscillatory dynamics are well quantified by ERD/ERS, so that motor imagery based BCI has attracted extensive interests. During tactile stimulation, the somatosensory cortex is the main active region of the brain and should indicate the brain's selective processing of the external tactile stimulation. In the STE-Group, the subjects were required to perform selective tactile sensation according to a cue (SS task), and were required to maintain the somatosensory attention on the corresponding hand (SAO task). Thus, the activation of brain regions in the SAO task mainly involved the sensory cortex, rather than the motor cortex, which is activated during the MI tasks. SAO and MI are different mental tasks, with the first corresponding to shifting and maintaining the somatosensory attentional resources to the focused body part (discriminative brain signals mainly from the sensory cortex), while the second corresponding to mentally simulating the kinesthetic movement of a limb (discriminative brain signals mainly from the motor cortex). Experimental studies that applied fNIRS and fMRI would be very beneficial in the future to compare SAO and MI.

Motor imagery is the mental simulation of the real movement, activating similar neural substrates as during the real movement. Similar to passive movement or motor imagery, which is utilized for motor recovery, the tactile sensation or imagined sensation (SAO) may have a potential for the functional recovery of degenerated sensory cortex. The benefits of SAO based BCI for somatosensory cortex rehabilitation will be investigated in future clinical trials.

V. Conclusion

In somatosensory modality, subjective attentional intention can be decoded based on SAO-related oscillatory activation, i. e. contralateral ERD stronger than ipsilateral ERD in the somatosensory brain area. The group-level classification accuracy of left and right SAO tasks both in the STE-Group and SAO-Group was above 75% (including online and offline performance), which makes the SAO a good candidate for a new BCI paradigm, alternative to the existing ones. Out of sensory stimulation, the SAO based BCI has reached a comparable performance as the tactile BCI based on selective sensation. The imagined sensation (SAO) translated from the tactile sensation, would be more applicable for its stimulus independent nature.

Acknowledgment

We thank all volunteers for their participation in the study. We thank Prof. Pete B Shull for the helpful suggestions. This work is supported by the National Basic Research Program (973 Program) of China (Grant No. 2011CB013305), the Science and Technology Commission of Shanghai Municipality (Grant No. 13430721600), the Research Project of State Key Laboratory of Mechanical System and Vibration MSV201607, and the National Natural Science Foundation of China (Grant No. 51375296).

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TNSRE.2016.2572226, IEEE Transactions on Neural Systems and Rehabilitation Engineering

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