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Freeing the visual channel by exploiting vibrotactile BCI feedback

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***Abstract*— Controlling a brain-actuated device requires the participant to look at and to split his attention between the interaction of the device with its environment and the status information of the Brain-Computer Interface (BCI). Such parallel visual tasks are partly contradictory, with the goal of achieving a good and natural device control. Is there a possibility to free the visual channel from one of these tasks? To address this, a stimulation system based on 6 coin-motors is developed, which provides a spatially continuous tactile illusion as BCI feedback, so that the visual channel can be devoted to the device. Several experiments are conducted in this work, to optimize the tactile illusion patterns and to investigate the influence on the electroencephalogram (EEG). Finally, 6 healthy BCI participants compare visual with tactile feedback in online BCI recordings.**

The developed stimulator can be used without interfering with the EEG. All subjects are able to perceive this type of tactile feedback well, and no statistical degradation in the online BCI performance could be identified between visual and tactile feedback.

***Index Terms*— BCI, EEG, Tactile Feedback, Vibration, Motor Imagery.**

I. INTRODUCTION

A Brain-Computer Interface (BCI) [13] can give people the possibility to control a computer or a device directly by using their brain activity, i.e. recorded non-invasively by means of the electroencephalogram (EEG). When controlling brain-actuated devices a split attention between the interaction of the device with its environment and the information from the BCI is required. Imagine controlling a wheelchair [3], [4] (or a telepresence robot [12]) with the BCI: on the one hand, you have to look where you want to drive your wheelchair, since you want to find your way and avoid obstacles. On the other hand, you have to be aware of the BCI feedback, which shows your current brain status and gives information about how close you are to delivering commands with the BCI. Therefore, both visual feedback loops are important for a successful control of applications, but are competing for the same resource: our visual channel. Furthermore, participants reported that this split attention is sometimes quite demanding for them [7].

Is there a chance to reduce the load or to free the visual channel from one of the components? Can we exploit other sensory channels besides the dominating and mostly used visual one? Auditory or somatosensory modalities have already been used in BCI research [10]. Since we are interested in controlling our applications in a self-paced way without any external cues, such evoked activities like auditory BCIs (listening to beep tones [11]), steady-state-somatosensory potentials (focused attention to variation in continuous stimulations [9]) or tactile P300 evoked potentials (focused attention to one out of several tactile stimulation pattern [2]) are not in our focus. Therefore, we concentrated on a solution for our self-paced (un-cued) motor imagery (MI) based BCI [8], where the subjects used the imagination of hand and/or foot movements to control the position of a feedback bar on a computer screen and subsequently various devices or applications [7]. We transferred the position of this feedback bar, which corresponds to the BCI classification probability in case of a visual BCI feedback, into a tactile feedback with stimulators on the neck of the participant. Instead of seeing the bar moving to the right or left and getting a feedback about the BCI, the participant received a tactile stimulation pattern which contains the same information, just without looking at it.

A similar approach was already presented in [5], but in their case they used magnetic actuators which interfered slightly with the electroencephalogram (EEG), and their spatial positioning was severely quantized due to the limited size and number of the actuators. Nevertheless, the same magnetic actuators have been successfully used in healthy participants: for stimulating on the upper and lower extremities or on the whole back of a participant via the usage of a vest [2]. But, since BCIs are mostly used for patients with spinal cord injuries (SCI) or other neurological diseases, restrictions in the somtasensory system are existent and stimulation on extremities or points far away from the central nervous system can be impossible because of the medical conditions. Therefore, we developed a tactile stimulation hardware based on simple coin motors (as used in mobile phones) which can be used for a spatially continuous tactile sensation on the neck of the participants, without creating magnetic or electrical artifacts in the EEG.

In this work, we present our tactile stimulation hardware; investigate different stimulation patterns to optimize the subject's sensations; analyze the influences of the tactile stimulation into the EEG, and compare visual and tactile feedback during online BCI experiments.

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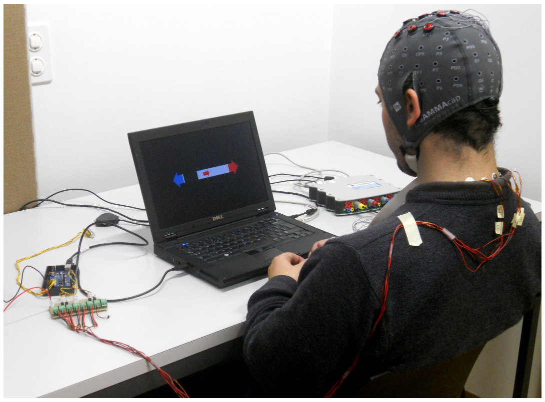

Fig. 1. Subject wears a cap with 16 active EEG electrodes over the motor cortex, which is connected to the EEG amplifier on the right side. The vibrotactile stimulators (six coin motors) are placed on the neck (slightly visible), which are controlled from an Arduino board on the left.

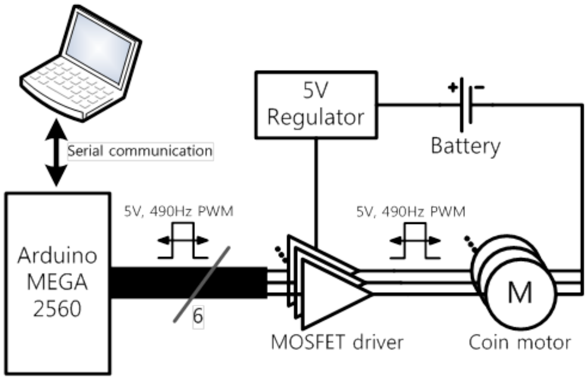

Fig. 2. Block diagram of the developed tactile BCI feedback system with six motors: the laptop is sending the value from the BCI feedback to the Arduino board, which is translating this value into a pulse-width modulation (PWM) of the six motors.

II. METHODS

A. Hardware and Software Setup

Six coin motors (Precision Microdrives, UK) with a diameter of 10 mm and a typical vibrational amplitude range of 0.5 g to 1.8 g are utilized for delivering tactile BCI feedback. The motors are attached in a horizontal line on the lower neck with a center point at the spine and about 2.5 cm of inter-motor-spacing (Fig. 1). The spatio-temporal vibration pattern of the stimulator is controlled by a laptop through a single-board microcontroller (Arduino, Italy) to indicate the output of the BCI classification. A pulse-width modulation (PWM) signal controls concurrently the amplitudes and the frequency of the vibration, changing from 110 Hz to 250 Hz (Fig. 2).

Two types of *protocols* are investigated, which convert the current BCI feedback to spatio-temporal vibration patterns (see Fig. 3). An optimal type of stimulation is important, since the spatial resolution of the touch sense is less than the resolution of the visual sense. In our applied 2-class BCI, the classification algorithm returns a probability value between 0 and 1 [6], whereby 1 correspond to the visual bar reaching the right side, 0 reaching the left side and 0.5 would be in the middle.

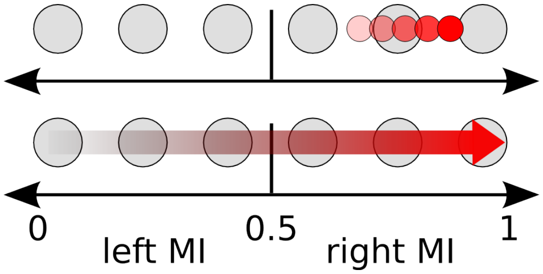

Fig. 3. Two types of protocol are investigated: point-based (top) and movement-based (bottom) convert the output of the BCI classification (probability value between 0 and 1) into a tactile pattern (indicated in red).

- The *point-based* protocol places an illusory tactile sensation at one point corresponding to the visual feedback position. For example, for a classifier probability of 0.75 the virtual sensation point is placed at the mid-point between the spine and the rightmost motor.
- In the *movement-based* protocol, the speed of illusory tactile feeling of movement via all motors from one side to the other is altered based on the BCI output. For example, a probability of 0.25 generates continuous left direction movements and that of 1 produces continuous right movements with a higher speed than that of 0.75.

In addition, for both protocols, the amplitude of the vibration increases as the probability approaches the extreme values.

B. Experiments

1) Characterization of the tactile illusion: The tactile illusion that places the virtual tactile sensation point in between the two real stimulation points [1] is employed in both protocols to increase the spatial resolution (since only 6 motors are utilized). This illusion point varies the position depending on the amplitude ratio of the real stimuli. For example, when two motors vibrate with the equal amplitude, the tactile illusion is located at the center, whereas when the amplitudes are unbalanced it moves closer towards the larger stimulation amplitude. Hence, if the amplitudes of two motors are properly varied over time, a smooth movement appears between the two motors.

To determine the appropriate shape of this amplitude variation, two types of preliminary recordings were conducted (i) between two motors and (ii) over all motors. Three subjects (23–25 years, 1 female) were asked to rank (1=low to 4=high) four stimuli that have different shapes of amplitude variation (linear and three logarithmic: log([1 3]), log([1 10]), log([1 30])) based on the characteristics of illusory movement: consistency of perceived strength, position of the illusion, and direction of the movement. In addition, to provide a constant increment of the perceived amplitude, the just-noticeable difference (JND) was measured for each subject.

2) Influence of vibrotactile stimulation on the EEG: The EEG was recorded from 64 channels distributed over the whole head with a very sensitive active EEG amplifier (BioSemi Instrumentation, The Netherlands) using a sampling rate of fs=2048 Hz, from DC to a low-pass filter of 417 Hz. Different tactile stimulation patterns (all motors / just left side / just right side / movement-based / no stimulation) were tested 30 times each. Every trial consisted of 5 seconds stimulation and 15 seconds rest. The spectrum was calculated for 1-second epochs (5 per stimulation period and 5 per rest) and averaged over the repetitions for each condition.

3) Online BCI experiments with vibrotactile feedback: A very important point is to verify if the subject can use this type of feedback, or if the tactile stimulation is interfering with their ability to control the BCI online. The brain activity was acquired via 16 EEG channels placed over the sensori-motor cortex (Fz, FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4, CP3, CP1, CPz, CP2 and CP4 according to the international 10-20 system with reference on the right ear and ground on AFz). The EEG was recorded with a g.USBamp (g.tec medical engineering, Austria) at fs=512 Hz, band-pass filtered 0.5–100 Hz and notch filter set to 50 Hz. From the Laplacian filtered EEG, the power spectral density was calculated. Canonical variate analysis was used to select subject-specific features, which were classified with a Gaussian classifier [6]. Decisions with low confidence on the probability distribution were filtered out and evidence was accumulated over time. More information about our BCI is given in [7].

In online experiments the output of the BCI is translated in a movement of the feedback, that informs the subjects about their current brain status. In the case of the visual feedback, the horizontal bar moves on a screen. In the case of tactile feedback, the motors vibrate and transmit the BCI output. Six healthy trained BCI subjects (29.5 ± 4.7 years, 1 female) compared the different feedback modalities: two runs with 15 left and 15 right cues each were performed for the following conditions: (i) normal visual feedback, (ii) visual and tactile feedback, (iii) only tactile feedback and (iv) again only visual feedback.

III. RESULTS AND DISCUSSION

A. Parameters for apparent tactile illusion and constant increase of perceived strength

Figure 4 shows the results of experiments to determine the shape of the amplitude variation. It shows that consistency increases in both cases, between two motors (narrow bars) and over all motors (wide bars), as the shape becomes more logarithmic over time [1]. However, there is a certain preference to the shape of log([1 3]) in direction when the tactile illusion moves between two motors, as it will be exploited in later experiments (see the highest values of the narrow bars in Fig. 4). For position, subjects preferred logarithmic shape. This results suggest that it is better to use the shape of log([1 3]) for the point-based protocol and the shape of log([1 10]) is appropriate for the movement-based protocol.

In the JND experiments, JNDs lie in the range of 5% to 20% for different locations and base amplitudes. As a result, Weber fraction is set to 0.2, such that the vibration amplitude varies depending on the BCI output. Note that, over a wide range of Weber fraction values, the shape of the exponential function remains almost unaffected when the function is scaled to the available ranges of the amplitude of the motors and that of the BCI output.

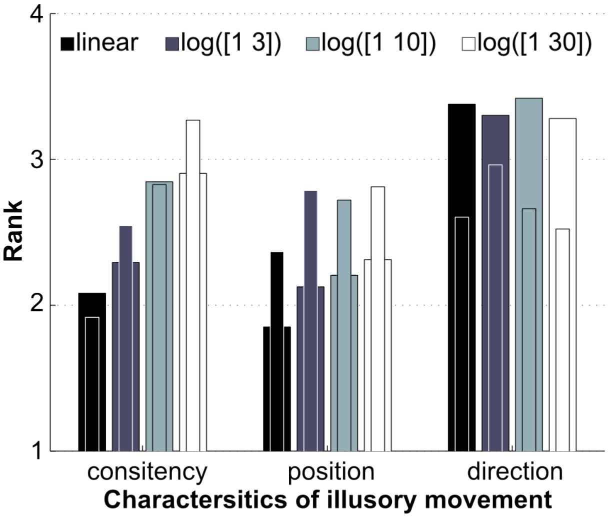

Fig. 4. Reported average ranks after normalization over each subject (1=low till 4=high). Narrow and wide bars represent the results of virtual movements between two motors and over all motors, respectively.

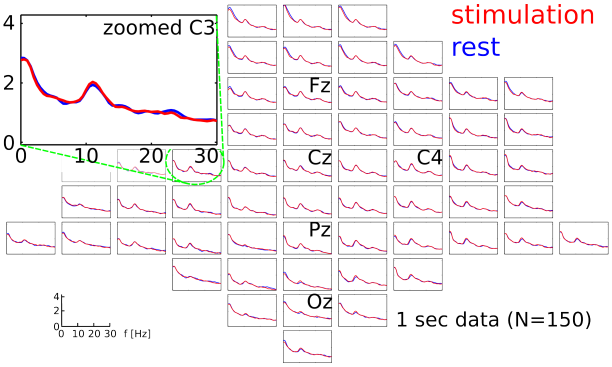

Fig. 5. Averaged EEG spectra during stimulation periods (in red) and rest periods (in blue) for one exemplary subject. Channel C3 is zoomed to give a closer look.

B. Influence of vibrotactile stimulation on the EEG

Figure 5 shows the EEG spectrum for one subject calculated for 1-second epochs (5 per stimulation period (second 0–5) and 5 per rest (second 6–11)) and averaged over the repetitions for each condition. One channel (C3) is zoomed in Fig. 5 to give a closer look on the conditions. No influence of the various stimulation patterns could be found in the EEG spectra while comparing stimulation to rest and over the conditions.

C. Online BCI experiments with vibrotactile feedback

Six BCI subjects compared the different feedback modalities online: (i) normal visual feedback, (ii) visual and tactile point-based feedback, (iii) only tactile point-based feedback

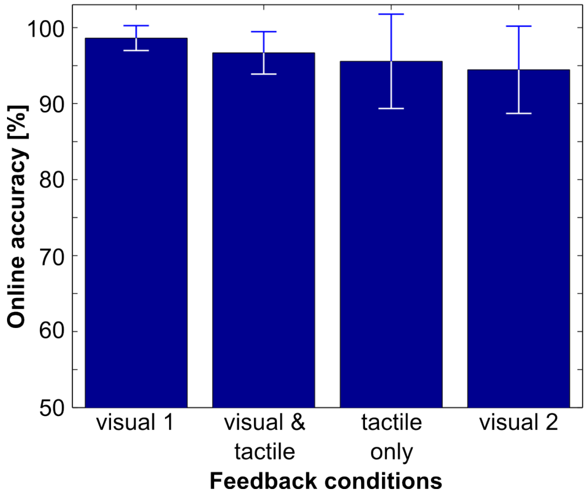

Fig. 6. Averaged online BCI accuracy of 6 subjects during the 4 feedback conditions: (i) only visual, (ii) visual and tactile, (iii) only tactile and (iv) again only visual (mean ± standard deviation).

and (iv) again only visual feedback. All subjects were able to control the BCI with all feedback modalities. Fig. 6 shows that no statistical difference in the performances could be identified, although the variance increased over the experimental time. This increase in variance, which is independent of the type of feedback (visual or tactile), is triggered by two subjects, who each had one run, where the BCI performance dropped. Although we want to mention, that "dropped" means only 5 wrongly classified trials out of 30 and the performance is still very high for BCI standards.

Additionally, two of our subjects tested the tactile movement-based feedback as well. In the only tactile movement-based condition (without visual feedback) a slight degradation of the performance appeared. Both subjects noticed that the point-based feedback was very intuitive, but in the movement-based protocol it was more difficult or it was not so straight forward to interpret the tactile sensation, especially in long-lasting trials. We think, that this problem occurs because the stimulators are placed along a straight line on the neck and are not placed completely around the neck (e.g by doubling the amount of motors). Therefore, no sensation of a circular running tactile pattern is achieved (e.g. to the right as in Fig. 3). The sensation is interrupted whenever the pattern reaches the rightmost motor and has to jump back to the leftmost motor. With an increasing BCI output the pattern starts to move faster and such jumps appear even more frequently. With low BCI outputs around 0.5 the sensation of moving to the left or right is quite strong, but diminishes when the output is close to 1 or 0. Since both subjects reported the same phenomena, we stopped testing this protocol online and focused on the point-based protocol, where such a jump and therefore break of the illusion cannot appear.

IV. CONCLUSIONS

In this work we presented the setup of a tactile stimulator which can be used to provide smooth spatially continuous tactile BCI feedback on the neck, without interfering with the EEG. Subjects were able to perceive this type of tactile feedback well and no statistical degradation in the online BCI performance could be identified between visual and tactile feedback conditions.

Our next steps involve the testing of our tactile feedback system directly with a brain-actuated device (e.g. a wheelchair or a robot). Afterwards, we should be able to investigate and quantify the benefits gained from the reduced visual workload, since the BCI feedback is no longer occupying the visual channel.

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