31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

An independent brain-computer interface based on covert shifts of non-spatial visual attention

Dan Zhang[1], Xiaorong Gao[1], *Member, IEEE*, Shangkai Gao[1], *Fellow, IEEE*, Andreas K. Engel[2] and Alexander Maye[2]

***Abstract*—Modulation of steady-state visual evoked potential (SSVEP) by directing gaze to targets flickering at different frequencies has been utilized in many brain-computer interface (BCI) studies. However, this paradigm may not work with patients suffering from complete locked-in syndrome or other severe motor disabilities that do not allow conscious control of gaze direction. In this paper, we present a novel, independent BCI paradigm based on covert shift of non-spatial visual selective attention. Subjects viewed a display consisting of two spatially overlapping sets of randomly positioned dots. The two dot sets differed in color, motion and flickering frequency. Two types of motion, rotation and linear motion, were investigated. Both, the SSVEP amplitude and phase response were modulated by selectively attending to one of the two dot sets. Offline analysis revealed a predicted online classification accuracy of 69.3±10.2% for the rotating dots, and 80.7±10.4% for the linearly moving dots.**

I. INTRODUCTION

A brain-computer interface (BCI) is a communication system which provides a direct information transfer channel between the human brain and a computer. With the help of BCIs, people who lost the normal capabilities for communicating with the environment are able to interact with a computer by executing certain mental tasks. Electroencephalography (EEG) is probably the most popular method used in BCI research for recording brain activity because of its high temporal resolution and noninvasiveness. A number of methods to extract the subjects' intentions from their EEG signals have been developed [1-3]. One of the most successful EEG-based BCI paradigms utilizes the modulation of the steady-state visual evoked potential (SSVEP). SSVEPs are automatic brain responses to flickering light, which faithfully follow the stimulation frequency. When the subject looks at one out of several targets flickering at distinct frequencies, SSVEP response at the corresponding frequency is enhanced. The modulation of SSVEP by this overt shift of attention can then be detected and translated into a control command [4-6]. However, SSVEP BCIs may not be accessible to patients with completely locked-in syndrome, since muscle activities such as gaze shifting plays an important role for SSVEP modulation. Therefore, SSVEP BCIs are categorized as 'dependent' BCIs [3, 7].

Visual attention may be differentiated as 'overt' versus 'covert' [8]. While overt attention is achieved by directly looking towards a stimulus, covert attention is defined as mentally focusing on a stimulus without any externally visible signs. Recently, efforts have been made to develop independent SSVEP BCIs based on covert shift of visual spatial attention [9, 10]. By selectively attending to one of two spatially distributed flicker stimuli, performances between 75% and 90% could be obtained [10, 11]. Using non-spatially, covert shift of attention, another recently proposed independent BCI yielded an accuracy around 60~70% in a binary selection task, where half of the subjects was able to operate the system [4].

For BCIs relying on spatial attention, target stimuli have to be spatially separated. This is problematic for a BCI employing covert attention shifts, as SSVEP response decreases significantly when the visual stimulus is out of the center of the visual field [12], and signal-to-noise ratio may become low. This problem does not occur with non-spatial attention, though. Multiple stimuli can be presented in the visual center in a superimposed manner. Non-spatial attention may provide, therefore, a better basis for developing independent BCIs.

In this paper, a novel BCI paradigm utilizing covert shifts of non-spatial visual attention is introduced. Two sets of random dots, with different colors, directions of motion, and flickering frequencies, but sharing the same region in the visual field are presented to the subjects. We conducted offline experiments to investigate whether modulation of SSVEP by shifting attention covertly to either of the two dot sets can be used as a control signal for an online BCI system.

II. EXPERIMENTAL METHODS

A. Subjects

Nine healthy subjects (3 female and 6 male), aged from 20 to 35 years old, participated in this study as volunteers. Eight of them were naïve to this experiment. All of them showed normal or corrected to normal eyesight.

Manuscript received April 7, 2009. This work was supported in part by the German Research Foundation through the Sino-German Research Training Group CINACS (www.cinacs.org) (AKE), in part by the Volkswagen Foundation, Grant "Representation" (AKE) and in part by National Nature Science Foundation of China (30630022).

[1] D. Zhang, X. Gao, and S. Gao (e-mail: gsk-dea@tsinghua.edu.cn) are with the Department of Biomedical Engineering at Tsinghua University, Beijing 100084, China.

[2] A. K. Engel and A. Maye are with the Department of Neurophysiology and Pathophysiology, University Medical Center Hamburg-Eppendorf, 20246 Hamburg, Germany.

B. Stimulation

The stimulus was displayed on an LCD monitor (DELL, USA) with 60Hz refresh rate and 1280×1024 resolution. A white dot was presented in the center of the screen to help subjects maintain fixation. Two sets of blue and red dots with equal brightness were randomly distributed in an annular area between 1° and 20° visual angle from the central fixation dot. Equal brightness was achieved by adjusting the pixel intensities of the displayed color for each subject before the experiments. Each dot subtended 0.3° of visual angle. The blue dots were flickered continuously at 10Hz (2:4 duty cycle), and the red dots at 12Hz (2:3 duty cycle) throughout each trial.

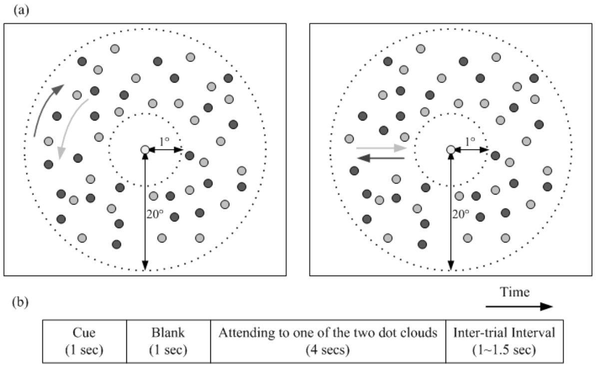

Fig. 1. The experimental paradigm, (a) Left: the 'rotating' stimulation; right: the 'moving' stimulation, (b) the timing sequence of one trial.

Two types of motion, 'rotating' and 'moving' dots, were used in our study, as illustrated in Fig. 1a. In the 'rotating' stimulation, all red dots were rotating counter-clockwise around the central fixation dot with an angular velocity of 1° per frame, while all blue dots rotated clockwise with the same velocity. In the 'moving' stimulation, all red dots were moving along the radial direction toward the fixation center (outside-in) with a velocity of 2 pixels per frame, while all blue dots moved in the opposite direction (inside-out) with the same velocity. Directing attention to all dots in either set was facilitated by color and motion coherence. Presentation of the stimuli was programmed in Matlab (The Mathworks, USA) using the Psychophysics Toolbox extensions [13, 14].

C. Procedure

The experiment was run in a normal office environment with no electromagnetic shielding. A 32-channel EEG amplifier (ActiveTwo system, Biosemi Instrumentation, Netherlands) was used to record the EEG at a sampling rate of 128Hz. The 32 electrodes were positioned according to the 10-20 system.

The timing of a single trial is shown in Fig. 1b. Subjects were instructed as to which set of dots they should attend by a colored cue presented in the center of the screen for 1 second before each trial. After the cue and an additional 1 second of blank screen, the stimulus was presented for 4 seconds. Subjects were asked to direct attention to the respective dot set while maintaining fixation on the central white dot. The inter-trial interval varied between 1 and 1.5 seconds. For each stimulation type, 25 trials in each condition were collected, presented in random order.

D. Data Analysis

In our paradigm, both, the to-be-attended and the unattended stimulus were simultaneously presented in the center of the visual field. Therefore, the modulation effects of SSVEP may differ from those SSVEP BCIs with overt visual attention shifts. In an explorative study the basic characteristics of SSVEP responses were analyzed. First, the DC components of the acquired EEG signals were removed by a 2Hz high pass filter (Chebyshev, 8th order). Then, both, amplitude and phase responses at the SSVEP frequencies were extracted by a fast Fourier transform for each trial and each EEG channel. Amplitude and phase were drawn in a polar plot for each trial to visually inspect the attentional modulation effects.

To find the EEG channels with the strongest attentional modulation, the squared Pearson product-moment correlation coefficient (r^2) was computed with both, amplitude and phase as feature values. Coefficients close to 1 indicate a linear relationship between the feature and the task, whereas for values close 0 there is no such correlation.

To evaluate the feasibility of implementing an online SSVEP BCI system, the amplitude and phase responses of occipital electrodes were selected as features for an offline classification. A Fisher linear classifier was employed and a 5×5 fold cross-validation accuracy test was carried out.

III. RESULTS

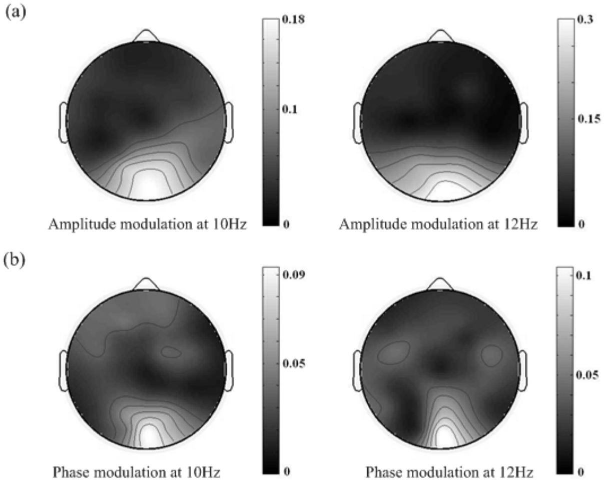

Fig. 2. Spatial mapping of r^2 value for stimulation with moving dots, note different scales are used for each plot.

The spatial mapping of r^2 values for amplitude and phase features in the 'moving' stimulation are shown in Fig. 2. The highest r^2 values are observed over central-occipital areas. A similar r^2 distribution is found for the 'rotating' stimulation. Polar plots of single trial SSVEP responses at electrode Oz are shown in Fig. 3. For both stimulations covert attention led to an enhancement in the amplitude response at the attended SSVEP frequency (Fig. 3a). Phase response was also modulated, resulting in different phase delays. However, inter-trial phase coherence did not change strongly between the attended and unattended conditions (Fig. 3b).

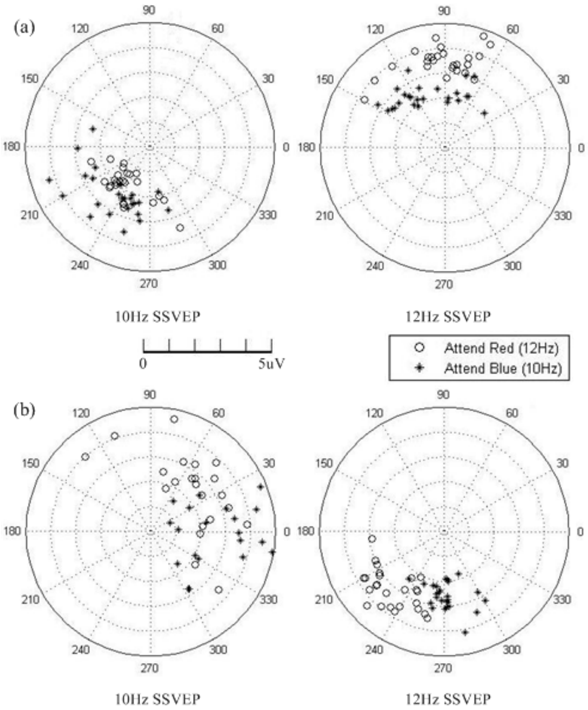

Fig. 3. Single-trial polar plot, (a) subject No.1, moving stimulation; (b) subject No.8, rotating stimulation.

Amplitude and phase values were used for offline classification, since we found both features to be modulated by attention. The highest classification accuracy was obtained for occipital electrode Oz, yielding an average performance of 80.7±10.4% for the 'moving' stimulation, and 69.3±10.2% for the 'rotating' stimulation. Individual performances are illustrated in Fig. 4.

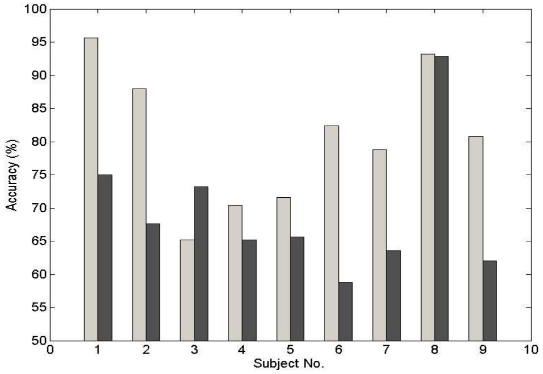

Fig. 4. Individual performances for the 'moving' stimulation (light gray) and the rotating stimulation (dark gray)

To investigate the minimal stimulation time needed for an acceptable performance, the window length for the offline analysis was reduced to 3, 2, and 1 seconds, respectively. As can be seen from Fig. 5, the performance increases with increasing window length. This trend is more obvious for the 'moving' than for the 'rotating' stimulation. At 4 seconds trial length both accuracies start to converge, suggesting that longer trials would not increase the average accuracy substantially. A paired t-test revealed a significantly higher average accuracy for the 'moving' stimulation than for the 'rotating' stimulation ($p<0.016$).

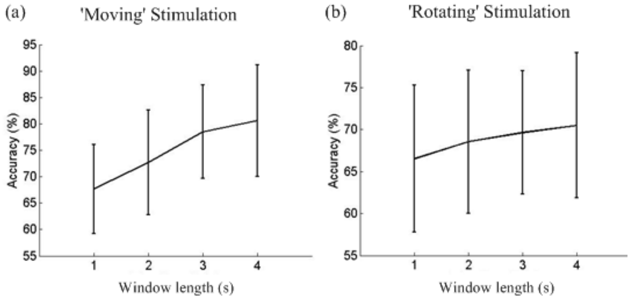

Fig. 5. Averaged classification accuracy for different sizes of the analysis window.

IV. DISCUSSION AND CONCLUSIONS

In our BCI paradigm we investigated the modulation effects of SSVEP amplitude and phase response for covert shifts of attention. Directing attention to one set of dots resulted in enhanced SSVEP amplitude response at the corresponding frequency. This finding is consistent with one previous study using a similar paradigm [15] and widely utilized in SSVEP BCIs. However, the modulation effect of SSVEP phase is different from SSVEP BCIs with overt attention shifts. Since the subject in those BCIs is not looking at the not-to-be-attended stimulus, the SSVEP response at this frequency is strongly reduced [12] and, consequently, the EEG signal represents mainly spontaneous brain activity. Therefore the phase responses should be randomly distributed. In our experiment attended and unattended conditions showed comparable inter-trial phase coherence, they only differed in phase delay. From the polar plot (Fig. 3b), the average phase difference at 12Hz SSVEP (one cycle of 83.3ms) was about 45° (1/8 cycle). The estimated temporal difference of SSVEP responses under the two attentional conditions is about 10ms (83.3 ms/cycle × 1/8 cycle). Time domain averages of 12Hz SSVEP (see Fig. 6) verified this estimation (about 1 sample point difference at 128Hz sampling rate, ~10ms). A similar modulation was reported in studies on visual spatial attention [16], but not on non-spatial attention [15]. Our findings here give the first report on phase shift of SSVEP modulated by non-spatial attention, and the first SSVEP BCI system using absolute phase values for classification.

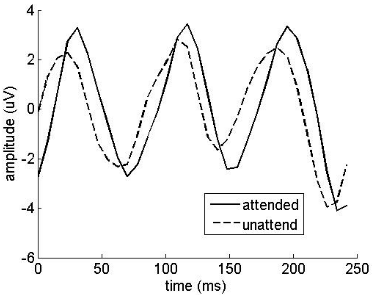

Fig.6. Time domain averages of 12Hz SSVEP, subject No. 8

It is worth noting that it is possible that the subjects subconsciously followed the movement of the attended dot set although they were told to focus on the central dot. However, even if the subjects rolled their eyes, SSVEP amplitude would likely not be affected because the two sets of dots were intermixed everywhere on the screen. The most likely neural mechanism to modulate SSVEP amplitude in this paradigm is non-spatial covert attention. Therefore, the proposed BCI system does not rely on muscle activity; it is an independent BCI system.

The comparison of the two stimulation types investigated in this study indicates a clear advantage for the 'moving' stimulation. Nevertheless, both stimuli show acceptable performance, especially subject No.8 shows predicted accuracies of >90% for both stimulation types. Thus, the performance of the proposed paradigm is encouraging for implementing an online independent SSVEP BCI system.

REFERENCES

[1] B. Z. Allison, E. W. Wolpaw, and A. R. Wolpaw, "Brain-computer interface systems: progress and prospects," Expert Review of Medical Devices, vol. 4, pp. 463-474, Jul 2007.

[2] M. A. Lebedev and M. A. L. Nicolelis, "Brain-machine interfaces: past, present and future," Trends in Neurosciences, vol. 29, pp. 536-546, Sep 2006.

[3] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain-computer interfaces for communication and control," Clinical Neurophysiology, vol. 113, pp. 767-791, Jun 2002.

[4] M. Cheng, X. R. Gao, S. G. Gao, and D. F. Xu, "Design and implementation of a brain-computer interface with high transfer rates," IEEE Transactions on Biomedical Engineering, vol. 49, pp. 1181-1186, Oct 2002.

[5] E. C. Lalor, S. P. Kelly, C. Finucane, R. Burke, R. Smith, R. B. Reilly, and G. McDarby, "Steady-state VEP-based brain-computer interface control in an immersive 3D gaming environment," Eurasip Journal on Applied Signal Processing, vol. 2005, pp. 3156-3164, 2005.

[6] M. Middendorf, G. McMillan, G. Calhoun, and K. S. Jones, "Brain-computer interfaces based on the steady-state visual-evoked response," IEEE Transactions on Rehabilitation Engineering, vol. 8, pp. 211-214, Jun 2000.

[7] A. Kubler, N. Neumann, J. Kaiser, B. Kotchoubey, T. Hinterberger, and N. P. Birbaumer, "Brain-computer communication: Self-regulation of slow cortical potentials for verbal communication," Archives of Physical Medicine and Rehabilitation, vol. 82, pp. 1533-1539, Nov 2001.

[8] R. D. Wright and L. M. Ward, "Orienting of Attention," Oxford University Press, 2008.

[9] B. Z. Allison, D. J. McFarland, G. Schalk, S. D. Zheng, M. M. Jackson, and J. R. Wolpaw, "Towards an independent brain-computer interface using steady state visual evoked potentials," Clinical Neurophysiology, vol. 119, pp. 399-408, Feb 2008.

[10] S. P. Kelly, E. C. Lalor, C. Finucane, G. McDarby, and R. B. Reilly, "Visual spatial attention control in an independent brain-computer interface," IEEE Transactions on Biomedical Engineering, vol. 52, pp. 1588-1596, Sep 2005.

[11] S. P. Kelly, E. C. Lalor, R. B. Reilly, and J. J. Foxe, "Visual spatial attention tracking using high-density SSVEP data for independent brain-computer communication," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 13, pp. 172-178, Jun 2005.

[12] E. E. Sutter, "The Brain Response Interface - Communication through Visually-Induced Electrical Brain Responses," Journal of Microcomputer Applications, vol. 15, pp. 31-45, Jan 1992.

[13] D. H. Brainard, "The psychophysics toolbox," Spatial Vision, vol. 10, pp. 433-436, 1997.

[14] D. G. Pelli, "The VideoToolbox software for visual psychophysics: Transforming numbers into movies," Spatial Vision, vol. 10, pp. 437-442, 1997.

[15] M. M. Muller, S. Andersen, N. J. Trujillo, P. Valdes-Sosa, P. Malinowski, and S. A. Hillyard, "Feature-selective attention enhances color signals in early visual areas of the human brain," Proceedings of the National Academy of Sciences of the United States of America, vol. 103, pp. 14250-14254, Sep 19 2006.

[16] S. T. Morgan, J. C. Hansen, and S. A. Hillyard, "Selective attention to stimulus location modulates the steady-state visual evoked potential," Proc Natl Acad Sci U S A, vol. 93, pp. 4770-4, May 14 1996.