Neuroscience Letters 449 (2009) 112–116

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

EEG-correlates of trait anxiety in the stop-signal paradigm

Alexander N. Savostyanov[a,b,*], Arthur C. Tsai[a], Michelle Liou[a], Evgeny A. Levin[b], Juin-Der Lee[a], Alexey V. Yurganov[b], Gennady G. Knyazev[b]

[a] Institute of Statistical Science, Academia Sinica , Taiwan
[b] State Research Institute of Physiology, Siberian Branch of Russian Academy of Medical Sciences, Russia

ARTICLE INFO

Article history:
Received 2 July 2008
Received in revised form 7 October 2008
Accepted 17 October 2008

Keywords:
Stop-signal paradigm
Trait anxiety
EEG oscillations

ABSTRACT

The relationship between trait anxiety and event-related EEG oscillatory reactions in the stop-signal paradigm was studied in 15 non-clinical subjects with average age of 26 years (13 men). In the paradigm, subjects responded to target stimuli by pressing one of the two choice buttons. In 30 out of 130 trials, target presentation was followed by a stop-signal, indicating that subjects had to refrain from a prepared motor response. The subject's level of anxiety was assessed using the State Trait Anxiety Inventory. Wide-band desynchronization (8–25 Hz) was found before button-press. It was sustained after the subjects pressed the button at 7–14 Hz frequency range. Also, synchronization at 15–25 Hz band occurred in 400–1400 ms after the button-press. Synchronization at lower frequencies (1–7 Hz) was also found during 0–700 ms after the stop-signal onset. Also, desynchronization at 8–20 Hz was found in 300–800 ms after stop-signal onset. The group with higher anxiety showed desynchronization at 10–13 Hz in 0–800 ms after the button-press, whereas the group with lower anxiety showed synchronization at the same frequency range. In 0–600 ms after stop-signal onset, desynchronization at 8–13 Hz was observed in the group with higher anxiety, whereas the group with lower anxiety demonstrated synchronization or weak desynchronization. Our findings support the Eysenck et al. [M.W. Eysenck, N. Derakshan, R. Santos, M.G. Calvo, Anxiety and cognitive performance: attentional control theory, Emotion 7(2) (2007) 336–356] theory that subjects with higher anxiety have more attentional control over reaction and increased use of processing resources as compared with lower anxiety subjects.

We investigated the influence of a trait anxiety level on parameters of EEG oscillations. Trait anxiety is usually defined as the inclination of a subject to perceive the environment as dangerous and to develop corresponding emotional, physiological and behavioral reactions [25]. In recent works, we have discussed relationships between trait anxiety and parameters of background EEG [11,12]. Studies on anxiety have tended to correlate this trait with the inclination of subjects to inhibit or activate different aspects of their behavior [8]. According to Eysenck et al. [7], subjects with higher anxiety showed a propensity to inhibit behavior in threat-related and novel conditions as compared with those with lower anxiety. It can be hypothesized that the differences in brain activity between higher and lower anxiety groups can be found in conditions in which they have to realize or stop an activity.

The experimental stop-signal paradigm (SSP) has been applied to investigate processes connected with activation and inhibition of motor reactions [16,18]. In last two decades the SSP was used mostly in clinical and behavioral studies [21]. It was also applied to study the neuronal basis of human behavior by means of EEG analysis [22,17,13]. However, until recently [5,14] there were no studies investigating the influence of personality traits of non-clinical subjects on reactions via SSP experiments. The aim of our research was to reveal correlates of anxiety levels in non-clinical subjects with patterns of EEG oscillations recorded under the visual SSP conditions.

Event-related perturbations of EEG spectral power (ERSPs) were used in our study to characterize brain activity in different experimental conditions. Based on functional roles of different rhythms [3], individual peculiarities of event-related EEG reactions can be interpreted in terms of between-subject variation in the functional organization of neural processes [6].

EEG data were obtained in 15 healthy right-handed Taiwanese subjects (13 males), aged 25–33 years (with average age 26 ± 3.0 years). All subjects were students or post-graduate students. All participants gave informed consent before enrollment into the

---

* Corresponding author at: Institute of Statistical Science, Academia Sinica 128, Academia Rd. Sec. 2, Taipei 115, Taiwan.
E-mail addresses: Alexander.Savostyanov@gmail.com, a-sav@ngs.ru (A.N. Savostyanov).

0304-3940/$ – see front matter © 2008 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.neulet.2008.10.084

study. The study was approved by the ethics committee in accordance with the Declaration of Helsinki.

The Chinese version of the State Trait Anxiety Inventory [24,25] (cSTAI) was used for measuring the trait anxiety level. A median split was applied to divide subjects into the relatively high- and low-anxiety groups. The cSTAI has been validated and its psychometric characteristics can be found in the study by Shek [24]. The face validity of cSTAI was doubly examined by a senior psychometrician, and we also interviewed a few subjects who voluntarily took the cSTAI. The final cSTAI used in the experiment had minor corrections on the Chinese translations of the original STAI based on the interview results. An application of STAI has been known to depend on social and cultural conditions, and, in particular, average anxiety scores differ between regions. For example, Iwata and Higuchi [9] demonstrated that persons from Japan show higher level of anxiety as compared with Americans. These differences could reflect distinctions as in intrinsic anxiety level, as in self-representation style, or both. For this reason, we can hardly evaluate the "true level" of anxiety for our participants. However, as all subjects are from the same culture, cSTAI could be applied to evaluate relative differences between subject groups. In the sequel, we will refer to subjects with relatively high- or low-anxiety level by holding the cultural-heredity constant.

During the experiment, each participant was seated comfortably in a chair with eyes open in a sound insulated dimly lit chamber. Visual stimuli were presented via a 24.4 cm × 18.3 cm monitor located 60 cm in front of the subject. The procedure was designed in a form of EEG-interfaced interactive computer game, during which the subject was motivated to make the maximum score. After 15 min of background EEG recording, participants performed 30 training trials of a choice reaction task in which they had to press left or right button after presentation of one of two pictures (a deer or a tank). The pictures (15 cm × 10 cm) were presented at the center of the computer monitor for 500 ms. Subjects should choose a weapon to strike a target (a rifle or an anti-tank rocket launcher) and shoot. Subsequently in 130 real trials of the stop-signal task, they had to refrain from pressing any button if a stop-signal (red bar, 3 cm × 2 cm, 250 ms in duration) was presented after the picture. In the instruction that was received before the task, the participants were told to respond as fast and accurately as possible. The deer and tank alternated randomly and the interstimulus interval randomly varied between 3.5 and 5.5 s. The stop-signal was randomly presented in 30 (approximately 23%) trials. The interval between onset of the picture and stop-signal was 250 ms. If a response was correct, the subject received additional points, and a deduction of points was applied to mistakes and to insufficient speed of reaction. Thus, two different conditions (Go and Stopping) were considered in the experimental procedure. EEGs were registered simultaneously with the game. The target and stop-signal presentations along with the subject's reactions were automatically labeled during EEG recording.

EEGs were recorded using 132 channels (128 EEG, VEOG, HEOG, EKG, EMG) via Ag/AgCl electrodes. The EEG electrodes were placed on 128 head sites according to the extended International 10–10 system and referred to Cz with ground at FzA. The Quik-Cap128 NSL was used for electrode fixation. The electrode resistance was maintained below 5 kΩ. The signals were amplified using "Neuroscan (USA)" amplifiers, with 0.1–100 Hz analog bandpass followed by a 50-Hz notch filter and continuously digitized at 1000 Hz.

To assess changes in spectral power, associated with button-press or the stop-signal onset, event-related spectral perturbations (ERSP) were calculated using the *timef* function in the EEGLAB toolbox (http://sccn.ucsd.edu/eeglab/). The ERSP [19] shows mean log event-locked deviations from baseline-mean power at each frequency. The method of ERSP calculation used in EEGLAB is described by Delorme and Makeig [4]. For time–frequency representation of EEG data, the wavelet transformation using the Morlet waveform as a mother wavelet was chosen.

The trials containing behavioral errors were rejected from analysis. Also, the first 30 trials from the training session for the choice reaction task without the stop-signals were rejected. For each subject 85–95 trials with button-press and 25–30 trials with the

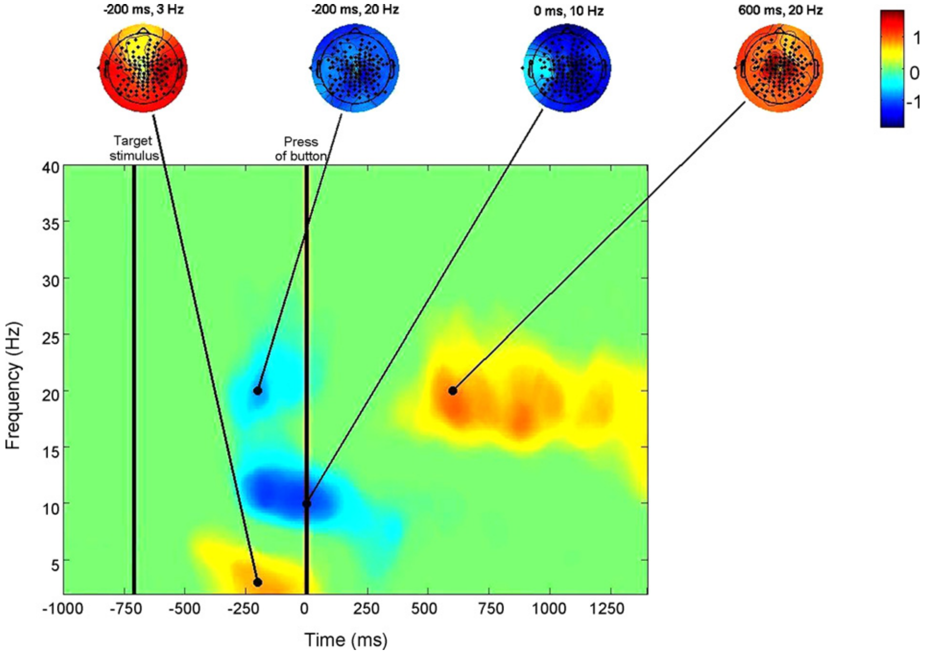

Fig. 1. ERSP associated with button-press in Go condition. ERSP plot shows values averaged for the whole group (15 subjects) with masked unsignificant reactions (green area). Four maps on the top represent topografic distribution of spectral power for time–frequency intervals with most significant reactions. Warm colors mean increase of power in relation to the reference time interval; cold colors—decrease. Left vertical lines represent average time of target stimulus onset. Right vertical lines (zero time point) correspond to the button-press.

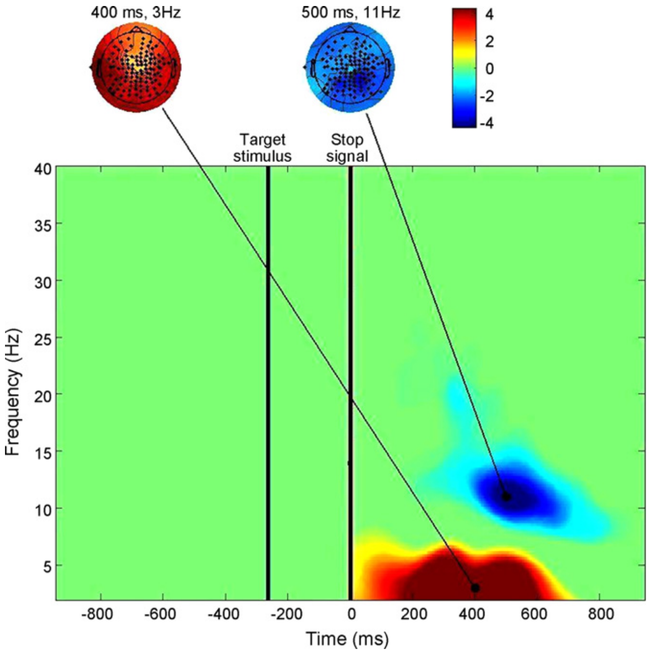

Fig. 2. ERSP associated with successful stopping. Left vertical line (at −250 ms) represents the target stimulus onset. Zero time point (right line) corresponds to stop-signal onset. All other designations are the same as in Fig. 1.

stop-signal were used. For the Go condition, on-going EEGs in the time intervals −1.7 to +1.7 s before and after the button-press were analyzed. For the Stopping condition, on the other hand, the EEGs in the time intervals −1.2 to +1.2 s before and after the stop-signal onset were used. Time interval from −0.95 to −0.25 s before target-stimulus onset was used for baseline-correction in both conditions.

A particular EEG-channel was removed, if there were irremovable artifacts in at least one subject, resulting in 108 EEG-channels for each subject and each experimental condition in the final data analysis. EEGs were preliminary band-pass filtered in 1–50 Hz using elliptic filters. Following the suggestion by Delorme and Makeig [4], re-reference and baseline adjustment procedures were performed during data preprocessing. Independent component analysis (ICA) was used for correction of eye-movement and eye-blinking artifacts [20]. Firstly, the component's weights were computed individually for each subject and each condition. The components corresponding to eye's artifacts were disclosed by visual inspection of component sets together with VEOG and HEOG records. Components of artifacts were removed in the preprocessing of EEGs.

After removing artifacts, we computed ERSP-indices separately for every EEG-channel, subject and experimental condition. The window size used was 512 samples (512 ms) for the lowest frequency. 177 frequencies were displayed from 2.0 to 44.9 Hz. Given an experimental condition, ERSPs were averaged across subjects and channels. The maps of ERSP cortical distributions were plotted for different time–frequency intervals of interest. The random permutation method with $p < 0.05$ significance level was applied in the statistical analysis of ERSPs for the Go and Stopping conditions [4].

Surrogate data distributions were constructed by selecting spectral estimates for each trial from randomly selected bootstrap latency windows in the specified epoch baseline (e.g., from −950 till −250 ms prior to the target stimulus onset). The 2.5 and 97.5 percentiles of these surrogate 'baseline' amplitude distributions were then taken as significance thresholds. Also, ERSP-patterns for a single-trial were viewed separately for each subject and condition. This procedure was used for additional checking of the reproducibility of the results.

Statistical significance of between-group differences in the time–frequency intervals was also assessed using the bootstrap method. Significance threshold was selected at $p < 0.05$. To avoid false positives from multiple comparisons, effects that were significant at only a few neighboring cells or a few channels were not interpreted. The ERSP values were averaged across 108 channels in each time–frequency point. The final p-values were calculated across all channels. Time–frequency plots of ERSP values were made for high- and low-anxiety groups as well as plots representing points of significant difference.

The average reaction time in the Go condition was 705 ms and had relatively large within- and between-subject (S.D. = 70) variation. For this reason, we centered our ERSP analysis at the moment of button-press and the stop-signal onset, but did not consider the target stimulus onset. Differences in reaction time between the low- and high-anxiety groups were insignificant. Also the two groups did not differ significantly in the number of missed button-presses in the Go condition, nor in the number of fail-to-stop trials.

EEG patterns in different experimental conditions were firstly investigated without reference to the anxiety level. In the Go condition, a decrease in EEG spectral power was found between approximately 250 ms before and 400 ms after the button-press (see Fig. 1). During movement preparation, this reaction covered a wide-frequency range in 8–25 Hz corresponding to boundaries of alpha and beta rhythms. After the button-press it was sustained at 7–14 Hz frequency range. Increases in spectral power were observed in a frequency range 15–25 Hz during 400–1400 ms after the button-press. Also spectral power was increased during movement preparation in 1–7 Hz band during −500 to 0 ms before button-press.

In the Stopping condition, significant desynchronization was observed in the frequency range 8–20 Hz during approximately 300–800 ms after the stop-signal onset (see Fig. 2). Besides, significant synchronization in the frequency range of 1–7 Hz was found during 0–700 ms after the stop-signal onset.

Significant differences between relatively high- (HA) and low- (LA) anxiety groups were found for both experimental conditions. In the Go condition, subjects with higher anxiety showed higher level of desynchronization (power decrease) before and after the button-press compared with lower anxiety subjects (see Fig. 3). Before button-press, desynchronization was significantly stronger for the HA group compared with the LA group. After the button-press, desynchronization was observed in the frequency range 7–13 Hz for the HA group, whereas the frequency range has been narrowed to 7–10 Hz for the LA group. Moreover, synchronization was observed immediately after the motor reaction in the LA group, while for the HA group, it appeared only 300 ms after the button-press.

In the Stopping condition, significant differences between groups in the level of synchronization were not observed. However, significant differences were observed for desynchronization in 8–13 Hz during 0–600 ms after the stop-signal onset (see Fig. 4). In the HA group, desynchronization was observed in this range whereas it was either absent (0–400 ms), or essentially lower (400–600 ms) in the LA group. The differences between groups were reduced through the time interval and disappeared in 650 ms after the stop-signal onset. In the first 200 ms, desynchronization was observed only in HA subjects whereas later it occurred in both groups.

The EEG patterns observed under the Go and Stopping conditions for the whole group are similar to those patterns found earlier in the auditory stop-signal tasks [17,13,14]. The horse-race model [18,2] provides theoretical interpretation of results obtained using the SSP. According to this model, two alternative neural processes compete after the stop-signal onset – activation and inhibition of

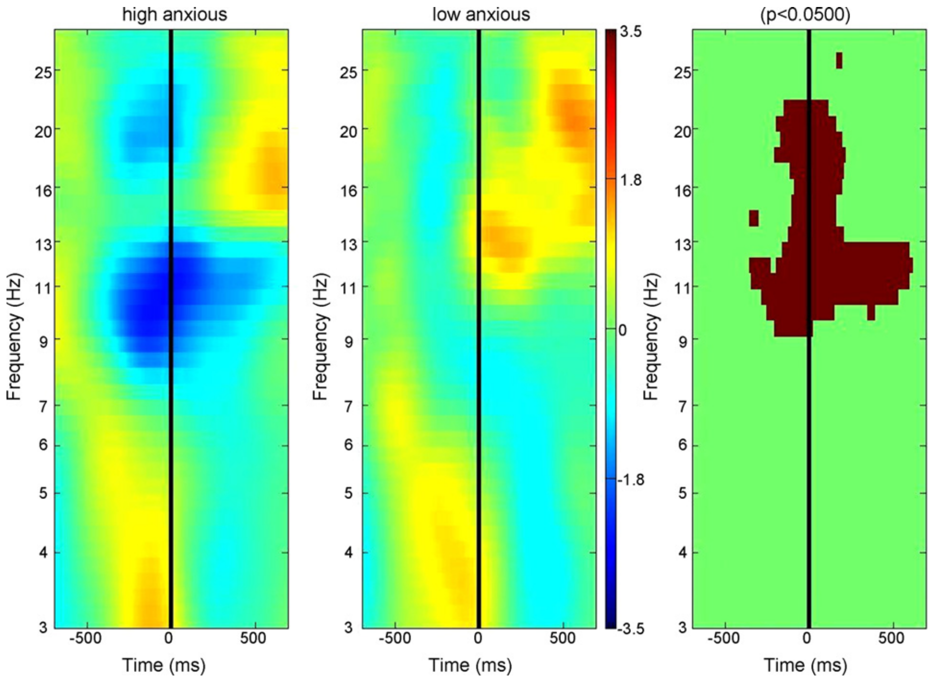

Fig. 3. ERSP associated with button-press in Go condition. Comparison between subjects with high-and low-anxiety levels. ERSP values are averaged for high- (6 subjects, left panel) and low- (9 subjects, central panel) anxiety groups. The right panel represents the time–frequency intervals with significant ($p < 0.05$) between-group differences (brown areas). Warm colors in left and central panels correspond to increase of power in relation to the reference time interval; cold colors—to decrease. Line at zero time point labels the button-press.

response. If activation processes win the “race”, subjects respond, and otherwise the reaction is successfully inhibited. In our study, under both experimental conditions, the relative spectral power increases in lower (delta and theta) and decreases in higher (alpha and beta) frequencies were observed. Relative decrease of spectral power in upper beta band (about 20 Hz) was clearly pronounced before and during movement. The pre-movement beta-ERD is considered to be a “classical” phenomenon, and the post-movement beta rebound was also observed in our study (see e.g. [26,1]). At the same time, it was shown that relative increase of power in the upper beta frequency band (about 20 Hz) is associated with increase of motor inhibition [23]. Concerning strong synchronization in slow rhythms after the stop-signal onset, analysis of auditory SSP task data [17,13] suggests that it could also be interpreted as a parameter reflecting the processes of motor response inhibition. Indeed, it was shown that ERP peaks, especially P3, after stop-signal have much larger amplitudes than after even Go stimuli [15], while delta/theta oscillations are the major contributors of late ERP waves [10].

In summary, we propose the following scheme: alpha-ERD, which is present in both conditions, corresponds to general activation and transient increase of arousal level and attention. ERD in the upper beta range in the Go condition is associated with movement preparation and execution. Movement preparation occurs also in stop-trials, but it is attenuated by inhibitory processes. And, finally, these inhibitory processes are represented in strong slow-wave activity after stop-signals. In the last case, we could not, however, exclude that elevated slow-wave synchronization reflects a general increase of activation caused by stop-signal onset rather than movement inhibition *per se*.

The differences in brain activity of subjects with higher and lower anxiety levels could be interpreted in terms of the Eysenck et al. [7] theory of attentional control of subject’s performance. According to this theory, high-anxiety persons have an inclination to suppress their behavior in risk-taking conditions. However, behavioral suppression is compensated by increase of attention to external stimuli and by results of own reactions. Persons with high-anxiety level try to control situations as much as possible. For this reason, their attention to the environment and the consequences of their own behavior is constantly maintained at a higher level.

In this study, subjects with higher anxiety showed significantly stronger alpha and beta desynchronization before the button-press than lower anxiety subjects. Desynchronization of upper alpha and low beta rhythms in higher anxiety subjects was still present after the button-press, whereas in lower anxiety ones, synchronization in these rhythms occurred right after the button-press. Recent works showed that higher anxiety persons have higher baseline level of alpha and beta activity in resting conditions [11,12]. Alpha activity in higher anxiety subjects was interpreted as “rhythm of readiness” reflecting a degree of subject’s preparedness to task performance. Beta oscillations also reflect processes of motor response preparation and sensorimotor integration [3]. Our new findings correspond well with this interpretation of the functional meaning of these EEG bands. We can hypothesize that higher spectral power in the resting condition is the reason for stronger desynchronization (in relation to baseline level) both before and after the response. In psychological terms it could be interpreted on the basis of the theory of attentional control. Higher anxiety persons are inclined to expend more efforts during preparation to task performance. Also, they continue controlling results of their reactions after trial is finished and it is reflected in stronger and more prolonged desynchronization in the alpha and beta frequency bands. On the contrary, lower anxiety subjects are not inclined to prolong control after finishing the response and thus their EEG-reaction rebound appears immediately after the button-press.

Subjects with higher anxiety made more effort to control not only locomotor reactions, but also the process of response inhibition. It is reflected in desynchronization in the alpha band which occurs after the stop-signal onset in high, but not in low-anxiety subjects. On the contrary, synchronization in theta frequency band is independent from anxiety level and is interpreted as index of

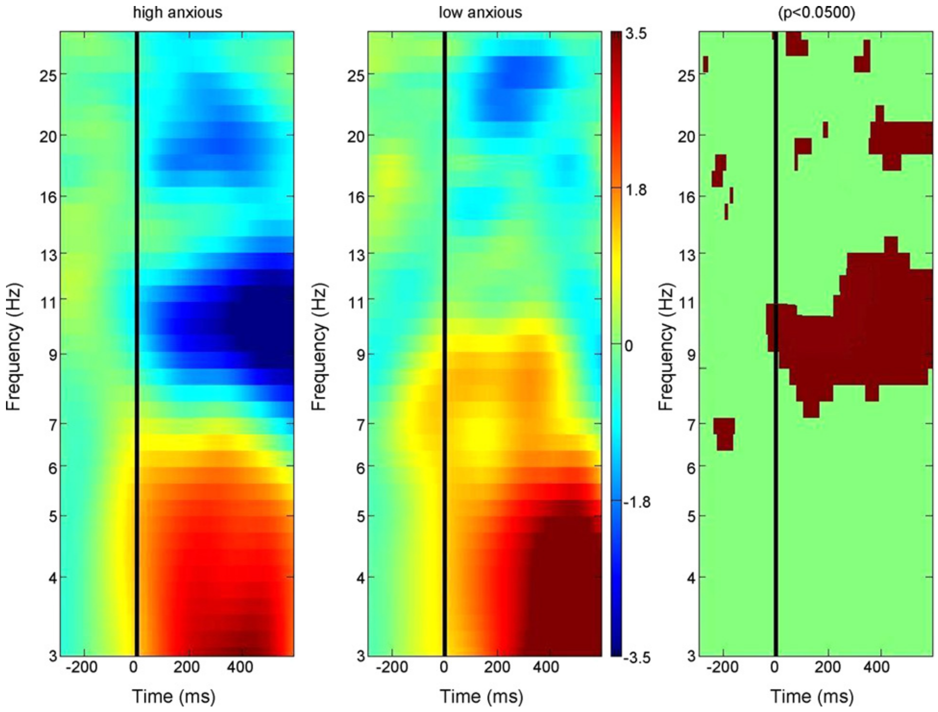

Fig. 4. ERSP associated with successful stopping. Comparison between subjects with high- and low-anxiety levels. Line at zero time point labels the stop-signal onset. All other designations are the same as in Fig. 3.

movement inhibition which necessarily occurs in successful stop-trials in both groups.

In summary, our EEG findings support the Eysenck et al. [7] theory about higher level of information processing in high-anxiety persons during tasks associated with directed attention. Indeed, trait anxiety levels have an impact on EEG-reactions, recorded in conditions of the SSP. Trait anxiety modulates attentional control and subjective evaluation of motor task execution.

Acknowledgments

This research was supported by grant NSC 96-2413-H-001-MY3 from the National Science Council (Taiwan). The authors are grateful to Dr. C.I. Kho for preparation of Chinese version of State-Trait Anxiety Inventory. Also, we are grateful to Professors C.D. Spielberger and John A.D. Aston for helpful comments on our study.

References

[1] M. Alegre, I.G. Gurtubay, A. Labarga, J. Iriarte, M. Valencia, J. Artieda, Frontal and central oscillatory changes related to different aspects of the motor process: a study in go/no-go paradigms, Exp. Brain Res. 159 (2004) 14–22.

[2] G.P. Band, M.W. van der Molen, G.D. Logan, Horse-race model simulations of the stop-signal procedure, Acta Psychol. (Amst.) 112 (2) (2003) 105–142.

[3] E. Basar (Ed.), Brain Functions and Oscillations. II. Integrative Brain Function. Neurophysiology and Cognitive Processes, Springer, Berlin, Heidelberg, 1999.

[4] A. Delorme, S. Makeig, EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis, J. Neurosci. Methods 134 (1) (2004) 9–21.

[5] A. Dimoska, S.J. Johnstone, Neural mechanisms underlying trait impulsivity in non-clinical adults: stop-signal performance and event-related potentials, Prog. Neuropsychopharmacol. Biol. Psychiatry 31 (2) (2007) 443–454.

[6] M. Doppelmayr, W. Klimesch, T. Pachinger, B. Ripper, Individual differences in brain dynamics: important implications for the calculation of event-related brain power, Biol. Cybern. 79 (1998) 49–57.

[7] M.W. Eysenck, N. Derakshan, R. Santos, M.G. Calvo, Anxiety and cognitive performance: attentional control theory, Emotion 7 (2) (2007) 336–356.

[8] J.A. Gray, N. McNaughton, The Neuropsychology of Anxiety: An Enquiry into the Functions of the Septo-hippocampal System, 2nd ed., Oxford University Press, Oxford, 2000.

[9] N. Iwata, H.R. Higuchi, Responses of Japanese and American university students to the STAI items that assess the presence or absence of anxiety, J. Per. Assesmen. 74 (2000) 48–62.

[10] S. Karakas, O.U. Erzengin, E. Basar, The genesis of human event-related responses explained through the theory of oscillatory neural assemblies, Neurosci. Lett. 285 (1) (2000) 45–48.

[11] G.G. Knyazev, A.N. Savostyanov, E.A. Levin, Anxiety and synchrony of alpha oscillations, Int. J. Psychophysiol. 57 (3) (2005) 175–180.

[12] G.G. Knyazev, A.N. Savostyanov, E.A. Levin, Uncertainty, anxiety, and brain oscillations, Neurosci. Lett. 387 (3) (2005) 121–125.

[13] G.G. Knyazev, E.A. Levin, A.N. Savostyanov, A failure to stop and attention fluctuations: An evoked oscillations study of the stop-signal paradigm, Clin. Neurophysiol. (3) (2008) 556–567.

[14] G.G. Knyazev, E.A. Levin, A.N. Savostyanov, Impulsivity, anxiety, and differences in evoked and induced brain oscillations, Int. J. Psychophysiol. 68 (3) (2008) 242–254.

[15] A. Kok, J. Ramautar, M.B. Deruiter, G.H. Band, K.R. Ridderinkhof, ERP components associated with successful and unsuccessful stopping in a stop-signal task, Psychophysiology 41 (2004) 9–20.

[16] J.S. Lappin, C.W. Erikson, Use of a delayed signal to stop a visual reaction-time response, J. Exp. Psychol. 72 (6) (1966) 805–811.

[17] E.A. Levin, A.N. Savostyanov, G.G. Knyzev, D.O. Lazarenko, Human brain oscillatory activity in condition of stop-signal paradigm, Bull. SB RAMS 24 (2007) 127–132.

[18] G.D. Logan, W.B. Cowan, K.A. Davis, On the ability to inhibit simple and choice reaction time responses: a model and a method, J. Exp. Psychol. Hum. Percept. Perform. 10 (2) (1984) 276–291.

[19] S. Makeig, Auditory event-related dynamics of the EEG spectrum and effects of exposure to tones, Electroencephalogr. Clin. Neurophysiol. 86 (1993) 283–293.

[20] S. Makeig, A.J. Bell, T.P. Jung, T.J. Sejnowski, Independent component analysis of electroencephalografic data, Adv. Neural Inf. Process. Syst. 8 (1996) 145–151.

[21] P. Murphy, Inhibitory control in adults with Attention-Deficit/Hyperactivity Disorder, J. Atten. Disord. 6 (1) (2002) 1–4.

[22] E. Naito, M. Matsumura, Movement-related potentials associated with motor inhibition as determined by use of a stop-signal paradigm in humans, Brain Res. Cogn. Brain Res. 2 (2) (1994) 139–146.

[23] B. Pastötter, S. Hanslmayr, K.H. Bäuml, Inhibition of return arises from inhibition of response processes: an analysis of oscillatory beta activity, J. Cogn. Neurosci. 20 (1) (2008) 65–75.

[24] D.T. Shek, The Chinese version of the State-Trait Anxiety Inventory: its relationship to different measures of psychological well-being, J. Clin. Psychol. 49 (3) (1993) 349–358.

[25] C.D. Spielberger, R.L. Gorsuch, R.E. Lushene, Manual for the State-Trait Anxiety Inventory, Consulting Psychologists Press, Palo Alto, CA, 1970.

[26] A.J. Stancak, G. Pfurtscheller, Event-related desynchronisation of central beta-rhythms during brisk and slow self-paced finger movements of dominant and nondominant hand, Cogn. Brain Res. 4 (1996) 171–183.