Transcutaneous Electrical Nerve Stimulation System for Improvement of Flight Orientation in a VR-based Motion Environment

Shiau-Ru Yang, Shi-An Chen, Shu-Fang Tsai, and Chin-Teng Lin, *Fellow, IEEE*

Abstract—**It is very important to reduce the possibility of spatial disorientation because spatial disorientation is a major cause of aircraft crashes. In this research, we assess the effect of transcutaneous electrical nerve stimulation (TENS) on spatial cognitive function by measuring physiological signals, including brain waves measured by electroencephalography (EEG). Through physiological signals such as brain waves, we can objectively understand a subject's cognitive state. Moreover, we use virtual reality technology to build 3D scenery that provides navigation clues in an environment with no visual reference frame. Using the virtual environment, we confirm that TENS lessens spatial disorientation. Across subjects and sessions, the parietal component of brain activity exhibited baseline elevation predominantly in the theta (4–7 Hz) and alpha (8–12 Hz) band as the subjects navigated. This study also found that subjects performed better after TENS in terms of behavioral and EEG data. The results facilitate understanding of the cognitive function of maintaining spatial orientation and development of a device for assisting pilots and reducing the occurrence of spatial disorientation.**

Index Terms—**theta, alpha, transcutaneous electrical nerve stimulation, navigation.**

I. Introduction

Spatial navigation is a crucial life skill, since way-finding and exploration of the environment are central to daily life. Spatial navigation is a complex task that requires the integration of information from different sensory inputs and the construction of a spatial representation of the environment. Specifically, for pilots flying aircraft, since the sky contains no visual reference frames, it is difficult to maintain a correct spatial representation of the environment. Therefore, in long-term flight or night-flying, the pilot can easily become spatially disoriented, that is, unable to determine the correct direction and orientation.

This work was supported in part by the Aiming for the Top University Plan of National Chiao Tung University, the Ministry of Education, Taiwan, under Contract 100W963
S. R. Yang is with the Department of Electrical Engineering,, National Chiao Tung University, Hsinchu, Taiwan.
Shi-An Chen is with the Department of Biological Science and Technology, National Chiao Tung University, Hsinchu, Taiwan.
C. T. Lin is with the Institute for Neural Computation, University of California San Diego, San Diego, USA.

In the past 20 years, many researchers studied the triggered take-off and upwind flight behavior of insects. Rapid escape in response to threatening visual stimuli and slow voluntary take-off based on the assessment of a stimulus reflect the animal's internal physiological state [1-3]. Olfactory cues elicit premeditated flight. Following takeoff, odor signals mediate upwind-oriented flight and guide insects toward the source [4, 5]. However, few studies have examined the human physiological state during flight.

From 1976 through 1992, pilot spatial disorientation contributed to 1,022 accidents and 2,355 fatalities. Spatial disorientation accidents accounted for approximately 15% of all military aviation accidents and were a major cause or factor in 15–16% of all fatal general aviation accidents, according to Collins & Dollar [6].

Human and animal studies suggest that acupuncture produces many beneficial effects throughout the central nervous system. However, the neural substrates of acupuncture's actions are not yet completely clear. Hui hypothesized that acupuncture recruits intrinsic brain networks involved in the regulation and integration of multiple brain functions to mediate its effects, and that the limbic system may play a major role. Functional MRI studies of acupuncture at *Hegu* (LI4) and *Zusanli* (ST36) have provided evidence in support of the hypothesis [7]-[10]. In response to those studies, we applied transcutaneous electrical nerve stimulation (TENS) at *Hegu* (LI4) and *Zusanli* (ST36).

The aim of this study is to investigate the effects of TENS on spatial disorientation caused by disturbances during flight operation. We estimated flying navigation performance during a flying task in a 3D virtual-reality- (VR-) based driving-simulation environment. Since there were no extra landmarks in the sky, subjects' navigation strategies were not biased by the environment. All subjects performed two sections. After section one, subjects took a rest and received mid-frequency electrotherapy. The 64-channel electroencephalographic (EEG) activity was recorded as subjects navigated in the tunnel and responded to homing direction selections and homing angular estimation. The EEG signals were processed and displayed in the spectro-temporal domain. The effects of the navigation strategy and performance on neural rhythms were compared and assessed in detail.

978-1-4673-0219-7/12/$31.00 ©2012 IEEE

II. Experimental Details

A. Subjects

A total of six subjects completed the flying experiment (ages 19–25, average age 22). They were paid to take part in the experiment. Only males were recruited because several studies have revealed inherent differences between the sexes in the subcortical structure involved in spatial navigation [11, 12]. None of the subjects had a history of neurological or psychiatric disease, and all were without drug or alcohol abuse. Subjects gave their written informed consent to participate in the study, which was approved by the Institutional Review Broad of Taipei Veterans General Hospital.

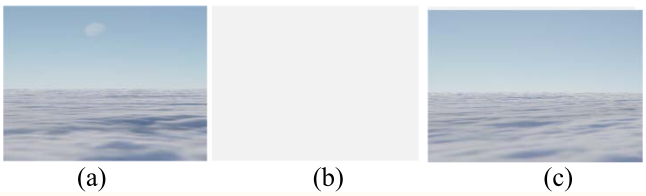

Fig. 1. Virtual sky environment in the experiment: (a) in the sky; (b) after entering turbulent flow and losing the sense of direction; (c) exiting turbulent flow and needing to locate the homing direction.

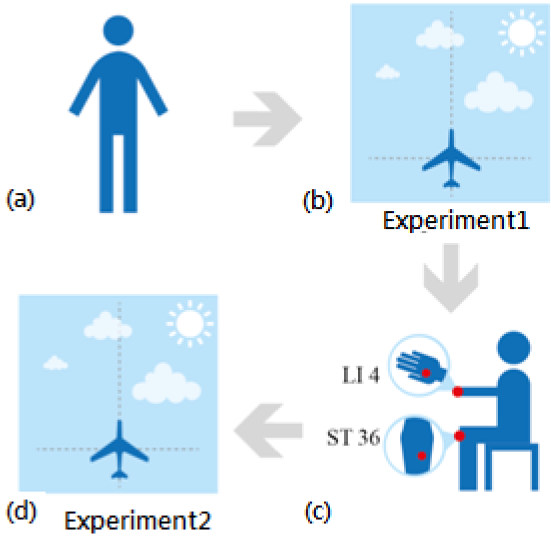

Fig. 2. Circuits and systems in the experiment. (a) Subject practices a flying task for 10 min. (b) Subject do Experiment1 for 10 min. (c) Subject was allowed to lie comfortably on the seat in a quiet environment and received TENS for 15 min. (d) Subject do Experiment2 for 10 min.

B. EEG Recording

The physiological data acquisition used 64 unipolar sintered Ag/AgCl EEG electrodes. All the electrodes were placed in an elastic cap according to the international 10-20 system. EEG data were recorded with the Scan NuAmps Express system (Compumedics Ltd., VIC, Australia) and digitized at 1000 Hz and a 32-bit quantization level.

C. Stimuli and Procedure

The subjects sat comfortably in a machine that was mounted in the center of a dimmed quiet room. Seven projection screens surrounded the car in a circle at a distance of 100 cm and provided a 206° frontal field of view (FOV) and 40° backward FOV comprising a virtual driving environment. All virtual scenery and physical motion were built and simulated by the World Tool Kit. Our driving simulator provides not only a high-fidelity VR scene, but also kinesthetic inputs and a realistic flight environment. These make the subjects feel that they are flying in a real aircraft in the real sky. The driving simulator consisted of a hydraulic hexapod motion platform that provided a tilt mechanism that simulated aircraft movement by supplying roll, yaw, and pitch motions.

Subjects were first required to practice a flying task for 10 min. We used the VR-based flying environment to investigate the EEG dynamics during sky navigation. In Experiment 1, subjects were exposed to animations of passage through a 3D virtual environment consisting of a sky segment [Fig. 1(a)] followed by entry into turbulent flow and losing the sense of direction [Fig. 1(b)]. Finally, they exited the turbulent flow and needed to indicate the homing direction [Fig. 1(c)]. The VR scene provided only visual flows of spatial translation and rotation. To determine whether TENS could enhance the task performance, every subject experienced TENS between the two experiments. TENS was applied at two traditional distal acupuncture points: *Hegu* (LI 4) and *Zusanli* (ST 36), as shown in Fig. 2. After Experiment 1, subjects were allowed to lie comfortably on the seat in a quiet environment and received TENS for 15 min. Then they performed Experiment 2. Experiments 1 and 2 consisted of the task shown in Fig. 1, and each lasted 10 min.

The aim of this study is to investigate the effects of TENS on spatial disorientation caused by disturbances during flight operation. We want to see the difference of performance between Experiment1 and Experiment2.

III. Data Analysis

A. Analysis of the Behavioral Data

After the turbulent flow segment, subjects were asked to adjust the direction as soon as possible. To investigate the task performance, the signed pointing error was analyzed across all subjects. Trails of signed pointing error exceeding 3 times the standard deviation were removed as outliers.

B. EEG Analysis

The continuous EEG signals were analyzed using MATLAB (The Mathworks, Inc.) and the open source EEGLAB toolbox (http://sccn.ucsd.edu/eeglab). The EEG signals were first down-sampled to 250 Hz for data compression and filtered to 0.5–50 Hz by a low-pass filter with a cut-off frequency of 50 Hz to remove line noise (60 Hz and its harmonic) and a high-pass filter with a cut-off frequency of 0.5 Hz to remove DC drift. Signal intervals containing electrode noise and large bursts of muscle artifacts were identified by visual inspection using the EEGLAB visualization tool and eliminated to enhance the signal-to-noise ratio.

C. *ICA and Event-Related Spectral Perturbations (ERSP)*

Independent component analysis (ICA) methods have been extensively applied to the blind source separation problem and were also confirmed to be a suitable solution to the problem of EEG source segregation, identification, and localization [13-15]. EEG signals were transformed into statistically maximally independent components (ICs) accounting for eye blinks, other eye movements, or muscle artifacts according to their scalp maps and activity profiles. Only brain-activity-related ICs were selected for further analysis.

ERSP is a type of time-frequency analysis first proposed by Makeig [16] that can reveal time-locked but not necessarily phase-locked event-related activities. ERSP analysis transforms a time-course signal into the spectral-temporal domain by short-term fast Fourier transform. Log power spectra were computed and then normalized by subtracting the baseline (straight tunnel segment) log mean power spectrum. The significance of deviations from the power spectral baseline was assessed by bootstrapping, a nonparametric permutation-based statistical method. Non-significant points were masked as zero; only significant ($p < 0.05$) perturbations were retained.

IV. Results

A. Behavioral Performance

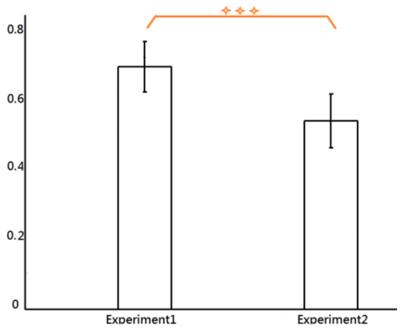

Fig. 3. Experimental cross-subject normalized error degree. After subjects received TENS, they decreased the degree of error and performed well.

The pointing errors were normalized in the range of [0, 1] degrees. Every subject exhibited better performance on Experiment 2 than on Experiment 1. Fig. 3 illustrates the cross-subject normalized signed pointing error for all trials among the two experiments. After subjects received TENS, they clearly decreased the degree of error and performed well. The data from both experiments were analyzed using a *t-test*, and we found Experiments made significantly more correct judgments.

B. Performance-related Brain Activity

Previous studies[17, 21] have demonstrated that changes in brain activity related to navigation performance were located in the parietal component. In this paper, we focus on the parietal component when presenting our results.

Fig. 4 (top panel) shows the grand mean of the ERSP image of the parietal IC cluster across six subjects in Experiments 1 and 2. Fig. 4(a) shows the parietal ERSP results for Experiment 1. Strong alpha activity near 10 and 20 Hz was suppressed slightly when turbulent flow began and was sustained until 400 ms. A different area of sustained activity in the alpha band (near 10 Hz) and at its first harmonic (20 Hz) increased strongly at the end of turbulent flow. These changes in the alpha band power were observed in all subjects. Fig. 4(b) shows the parietal ERSP results for Experiment 2. The alpha activity was stronger than in Experiment 1 [Fig. 4(a)]. It was sustained for longer than in Experiment 1 (about 100 ms), and the increase in alpha activity appeared earlier (also about 100 ms).

Fig. 4(c) shows the difference between Experiment 1 and Experiment 2. The alpha band activity near 13 Hz increased at the beginning of turbulent flow, followed by a low-band theta increase. At the end of turbulent flow, the power band increased near 13 Hz and decreased near 18 Hz.

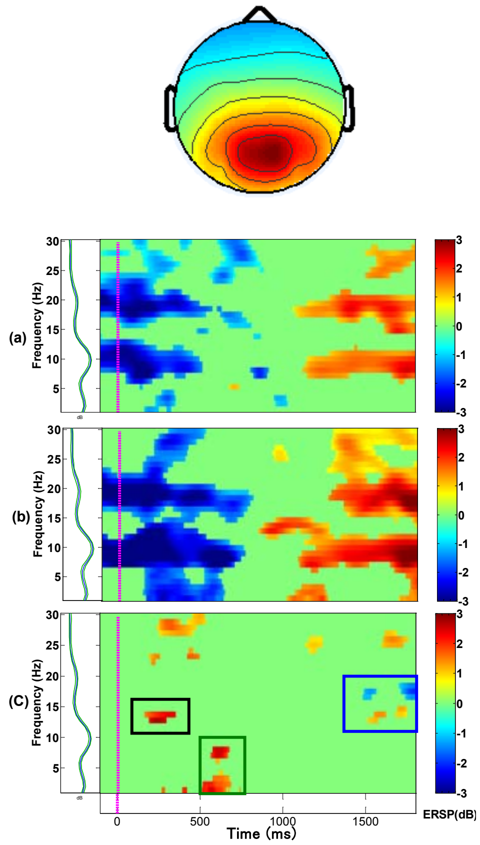

Fig. 4. (top) Grand mean of the ERSP images revealing significant differences. (bottom) Average component map of the parietal cluster across six subjects. Epochs are aligned to the onset of turbulent flow (pink dashed lines. (a) Experiment 1; (b) Experiment 2; (c) Experiment 1 minus Experiment 2. The alpha activity in Experiment 2 was stronger than in Experiment 1. It was sustained for longer than in Experiment 1, and the increase in alpha activity appeared earlier.

V. Discussion And Conclusion

In the EEG data analysis, the absolute theta band (4–8 Hz) power was extracted by complex demodulation. Theta oscillations in the human brain have also been observed frequently during spatial navigation [18-20]. The sensorimotor integration hypothesis proposes that theta oscillations coordinate sensory information with a motor plan that directs way-finding behavior to known goal locations. Hence, the motor plan is updated on the basis of incoming sensory information. Moreover, modulation of alpha band (8–13 Hz) activity has been observed during navigation, depending on the complexity of T-mazes [22], and during route-planning periods [20], with increases and decreases in alpha activity interpreted in cortical excitability and increased readiness of cortical source domains to process incoming information, respectively [23]. The parallel alpha-blocking pattern for the parietal component cluster resembled those for occipital clusters, which is consistent with a model in which optic flow activates the dorsal cuneus [24]. The perceptual division of labour between the various activated areas cannot be directly inferred, though it is a reasonable supposition that the parietal activation reflects the utility of optic flow for guiding self-motion [25].

VI. Conclusion

Behavioral analysis revealed that subjects can perform better after TENS treatment than before. From this and the EEG analysis, we found that after subjects received TENS, the brain activity strengthened, and the alpha band (near 10 Hz) and its first harmonic (20 Hz) of the parietal component was sustained for longer than before the application of TENS. we can conclude that TENS can enhance the subjects' navigation ability.

References

[1] ALLEN, M. J., GODENSCHWEGE, T. A., TANOUYE, M. A., and PHELAN,P., "Making an escape: development and function of the Drosophila giant fibre system," *Semin. Cell Dev. Biol.*, 17:31–41, 2006.

[2] CARD, G. and DICKINSON, M. H., "Visually mediated motor planning in the escape response of Drosophila," *Curr. Biol.,* 18:1300–1307, 2008

[3] TRIMARCHI, J. R. and SCHNEIDERMAN, A. M., "Different neural pathways coordinate Drosophila flight initiations evoked by visual and olfactory stimuli," *J. Exp. Biol.,* 198:1099–1104, 1995

[4] BUDICK, S. A. and DICKINSON, M. H., "Free-flight responses of Drosophila melanogaster to attractive odors," *J. Exp. Biol.,* 209:3001–3017, 2006

[5] CHOW, D. M. and FRYE, M. A., "Context-dependent olfactory enhancement of optomotor flight control in Drosophila," *J. Exp. Biol.,* 211:2478–2485, 2008

[6] Collins, W.E., and C.S. Dollar, "Fatal General Aviation Accidents Involving Spatial Disorientation," 1976-1992, *FAA Aviation Medicine Report ADA313864*, 1996.

[7] Fang JL, Nixon E, Liu J, Hui KKS., "The limbic-cortical system and pain neuromatrix: Deactivation by acupuncture, activation by pain - an fMRI study at LV3," Abstract. Society for Neuroscience 2007 Annual meeting in San Diego, 2007

[8] Hui KKS, Liu J, Chen AJ, Wu MT, Rosen BR, Kwong KK, "Effects of acupuncture on human limbic system and basal ganglia measured by fMRI," *Neuroimage*, 5:S226,1997b.

[9] Hui KKS, Liu J, Chen AJ, Makris N, Gollub RL, Kennedy DN, Moore CI, Rosen BR, Kwong KK, "Acupuncture modulates the limbic system and subcortical gray structures of the human brain-direct evidence by fMRI," *Neuroimage*, 1998.

[10] Hui KKS, Liu J, Makris N, Gollub RL, Chen AJ, Moore CI, Kennedy DN, Rosen BR, Kwong KK, "Acupuncture modulates the limbic system and subcortical gray structures of the human brain: Evidence from fMRI studies in normal subjects," *Hum Brain Mapp.,* 9:13–25, 2000.

[11] G. Grön*, et al.*, "Brain activation during human navigation: Gender-different neural networks as substrate of performance," *Nature neuroscience,* vol. 3, pp. 404-408, 2000.

[12] B. Kolb and J. Cioe, "Sex-related differences in cortical function after medial frontal lesions in rats," *Behavioral Neuroscience,* vol. 110, pp. 1271-1281,1996.

[13] T. Lee, M. Girolami, and T.J. Sejnowski, "Independent Component Analysis Using an Extended Infomax Algorithm for Mixed Subgaussian and Supergaussian Sources," *Neural Computation,* vol. 11, pp. 417-441,1999.

[14] T. Jung et al., "Analysis and visualization of single-trial event-related potentials," *Human Brain Mapping,* vol. 14, pp. 166-185,2001.

[15] M. Naganawa et al., "Extraction of a plasma time-activity curve from dynamic brain PET images based on independent component analysis," *Biomedical Engineering, IEEE Transactions on,* vol. 52, pp. 201-210, 2005.

[16] S. Makeig, "Auditory Event-Related Dynamics of the EEG Spectrum and Effects of Exposure to Tones," *Electroencephalography and Clinical Neurophysiology,* vol. 86, pp. 283-293, 1993.

[17] Te-Cheng Chiu, Klaus Gramann, Li-Wei Ko1, Jeng-Ren Duann, Tzyy-Ping Jung, Chin-Teng Lin, "Alpha modulation in parietal and retrosplenial cortex correlates with navigation performance," *Psychophysiology*, 2010.

[18] Caplan, J. B., Madsen, J. R., Schulze-Bonhage, A., Aschenbrenner-Scheibe, R., Newman, E. L., & Kahana, M. J., "Human theta oscillations related to sensorimotor integration and spatial learning," *Journal of Neuroscience*, 23, 4726–4736, 2003.

[19] Lisman, J., & Buzsáki, G. , "A neural coding scheme formed by the combined function of gamma and theta oscillations," *Schizophrenia Bulletin*, 34, 974–980, 2008.

[20] de Araújo, D. B., Baffa, O., & Wakai, R. T., "A magnetoencephalography study," *Journal of Cognitive Neuroscience,* 14, 70–78, 2002.

[21] Jacobs, J., Korolev, I. O., Caplan, J. B., Ekstrom, A. D., Litt, B., Baltuch, G., et al., "Right-lateralized brain oscillations in human spatial navigation," *Journal of Cognitive Neuroscience*, 22, 824–836, 2010.

[22] Caplan, J. B., Madsen, J. R., Raghavachari, S., & Kahana, M. J. , "Distinct patterns of brain oscillations underlie two basic parameters of human maze learning," *Journal of Neurophysiology*, 86, 368–380, 2001.

[23] Pfurtscheller, G, "Functional brain imaging based on ERD/ERS," *Vision Research*, 41, 1257–1260, 2001.

[24] Gramann, K., Onton, J., Riccobon, D., Mueller, H.J., Bardins, S., Makeig, S., "Human brain dynamics accompanying use of egocentric and allocentric referenceframes during navigation," *J. Cogn. Neurosci,.* 22, 2836–2849, 2009.

[25] de Jong, B. M., Shipp, S., Skidmore, B., Frackowiak, R. S., & Zeki, S. "The cerebral activity related to the visual perception of forward motion in depth," *Brain*, 117,1039–1054, 1994