Mental fatigue from sustained attentional demand alters the properties of small-world functional networks

Lim, J., Sun, Y., Kwok, K., Bezerianos, A.

***Abstract*— Mental fatigue is often accompanied by suboptimal task performance, which has motivated researchers to study its neural basis. Here, we use network analysis to investigate functional cortical maps at the start and end of a 20-minute test of sustained attention. We observed overall increases in path length that were correlated with performance declines, as well as an asymmetric change in connectivity between frontal and posterior attentional regions.**

I. Objective

A number of prior studies have demonstrated the critical importance of a right-lateralized fronto-parietal network in sustaining high levels of vigilance and performance under these conditions [1,2]. However, the use of whole-brain network analysis [3] approaches is still relatively novel, with only several reports of fatigue-related differences found using these methods [4,5]. To add to this body of knowledge, we investigated changes in cortex-wide functional connectivity in the early and late stages of performance of a mentally demanding attentional task.

II. Methods

Participants' (N=26) brain activity was recorded using high-density 64-channel EEG while they performed a 20-minute version of the Psychomotor Vigilance Test (PVT), a challenging attention task with a high signal load [5]. Performance declines were estimated using a least-squares fit to individual reaction times plotted against time. We investigated the differences in connectivity patterns in the low alpha EEG band (8-10 Hz) between the rested (first 5 minutes of task) and fatigued (last 5 minutes of task) states. Functional connectivity graphs were constructed using partial directed coherence, and then converted into a weighted directed graph from which small-world metrics were calculated. To investigate the specific brain areas responsible for fatigue-related change, we reconstructed source activity via a minimum norm estimate before estimating connectivity among 26 pre-defined regions of interest (ROIs). Multivariate analysis of variance was used to test for differences between states in our variables of interest.

J.L. is with the Singapore Institute for Cognitive Science and Neurotechonologies (SINAPSE) and the Department of Psychology, National University of Singapore (phone: +65 98596770; e-mail: tsllzj@nus.edu.sg).

Y.S. (e-mail: lsisu@nus.edu.sg), K.K. (email: kenkwok@nus.edu.sg) and A.B. (email: tassos.bezerianos@nus.edu.sg) are with the Singapore Institute for Cognitive Science and Neurotechonologies (SINAPSE), Singapore.

III. Results

Reaction times on the PVT were significantly slower at the end than at the beginning of the task ($F_{1,\,25} = 11.84$, $p = 0.0011$). Mean α_1PDC values showed a marginally significant ($F_{1,25} = 3.90$, $p = 0.059$, $\eta_\rho^2 = 0.135$) increase from the first to last five minutes of the PVT. Among the network variables tested, significant increases were found in path length ($F_{1,\,25} = 8.79$, $p = 0.007$, $\eta_\rho^2 = 0.26$), and mean normalized weighted characteristic path length ($F_{1,25} = 5.29$, $p = 0.03$, $\eta_\rho^2 = 0.18$). These increases were correlated with the slope of performance decline ($r = -0.43$, $p = 0.04$). Inter-hemispheric cortical connections decreased significantly ($F_{1,25} = 5.93$, $p = 0.018$) in the 4^{th} quartile while intra-hemisphere connections did not ($F_{1,25} = 1.21$, $p = 0.28$). Finally, we found significant differences in ipsilateral connectivity between dorsolateral prefrontal cortex and cingulate cortex, suggesting a specific decoupling of frontal from posterior regions in the fatigued state.

IV. Conclusions

Increases in path length may represent a useful index of mental fatigue. Change in this metric may arise because of reduced efficiency in nodes central to the maintenance of sustained attention, and decreased interhemispheric communication between frontal and posterior brain regions. As network analysis is sensitive to these changes over relatively short time scales, it may be a useful tool to detect such brain states for on-the-job applications.

Acknowledgment

This research was supported by NEUROEN grant R394000059232 to K. K.

References

[1] Paus, T., Zatorre, R. J., Hofle, N., Caramanos, Z., Gotman, J., Petrides, M., et al. (1997). Time-related changes in neural systems underlying attention and arousal during the performance of an auditory vigilance task. *J. Cogn. Neurosci., 9*(3), 392-408.

[2] Lim, J., Wu, W. C., Wang, J., Detre, J. A., Dinges, D. F., & Rao, H. (2010). Imaging brain fatigue from sustained mental workload: an ASL perfusion study of the time-on-task effect. *Neuroimage, 49*(4), 3426-3435.

[3] Bullmore, E., & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. *Nat. Rev. Neurosci., 10*(3), 186-198.

[4] Breckel, T. P., Thiel, C. M., Bullmore, E. T., Zalesky, A., Patel, A. X., & Giessing, C. (2013). Long-term effects of attentional performance on functional brain network topology. *PLoS One, 8*(9), e74125.

[5] Giessing, C., Thiel, C. M., Alexander-Bloch, A. F., Patel, A. X., & Bullmore, E. T. (2013). Human Brain Functional Network Changes Associated with Enhanced and Impaired Attentional Task Performance. *J. Neurosci., 33*(14), 5903-5914.