Information Flow and Coherence of EEG During Awake, Meditation and Drowsiness

Chamila Dissanayaka[1], Eti Ben-Simon[2, 3], Michal Gruberger[2, 4], Adi Maron-Katz[2, 3], Talma Hendler[2- 4]
Ramiro Chaparro-Vargas[1], Dean Cvetkovic*[1] *(Member)*

Abstract - **A comparison of coupling (information flow) and coherence (connectedness) of the brain regions between human awake, meditation and drowsiness states was carried out in this study. The Directed Transfer Function (DTF) method was used to estimate the coupling or brain's flow of information between different regions during each condition. Welch and Minimum Variance Distortionless Response (MVDR) methods were utilised to estimate the coherence between brain areas. Analysis was conducted using the EEG data of 30 subjects (10 awake, 10 drowsiness and 10 meditating) with 6 EEG electrodes. The EEG data was recorded for each subject during 5 minutes baseline and 15 minutes of three specific conditions (awake, meditation or drowsiness). Statistical analysis was carried out which consisted of the Kruskal-Wallis (KW) non-parametric analysis of variance followed by post-hoc tests with Bonferroni alpha-correction. The results of this study revealed that a change in external awareness led to substantial differences in the spectral profile of the brain's information flow as well as it's connectedness.**

I. Introduction

In order to understand the propagation of Electroencephalograpic (EEG) signals it is essential to investigate the information flow and coupling between brain regions. Past studies have revealed a parallel mode of activity in multiple cortical areas during a large array of cognitive processes [1], [2] & [3]. However, these studies mostly focused on task related states in which subjects were fully conscious of the external environment. In this study we assumed that vast changes in information flow will also occur in states which differ in their level of awareness to the external environment, as known to occur during sleep [4].

In order to explore this assumption we examined the information flow between brain regions in three different conditions: awake, meditation and drowsiness. A certain level of detachment from external environment is required for each of these conditions and it will allow us to investigate the associated alterations related to coupling and connectedness of EEG channels within each state.

Since meditation, drowsiness and awake are placed around sleep onset, they are accompanied by significant changes in the EEG spectrum [5]. We decided to examine specific frequency bands: delta1 (0.5-2.0 Hz), delta2 (2.0-4.0 Hz), theta (4.0-8.0 Hz), alpha (8.0-14.0 Hz), sigma (12.0-14.0 Hz), beta (14.0-30.0 Hz) and gamma (30.0-45.0 Hz). In each state we explored the EEG activity-flow in a given direction and the functional connectedness between brain regions. For the estimation of connectedness (coherence), Welch and MVDR methods were compared, whilst the DTF method was applied for the estimation of coupling or brain's flow of information between distributed regions.

The Direct Transfer Function (DTF) method was first introduced by Kaminski and Blinowska [6] and is based on multivariate autoregressive (MVAR) model [7]. The direction of information flow and coupling relationship of multiple interacting EEG channels can only be found if those channels are evaluated simultaneously. For that reason DTF is used to analyse multi-channel EEG data. Furthermore the autoregressive model is capable of extracting information from a noise contaminated signal [6]. The DTF is highly robust to noise, and its results are not influenced by an addition of external noise.

The current study applied two approaches of coherence analysis. The first approach was MATLAB's 'mscohere' algorithm which is based on Welch's method [8]. The Welch estimator can be computed by FFT and is commonly used in spectral estimation. Minimum Variance Distortionless Response (MVDR) coherence analysis was further applied in order to estimate the connectedness of EEG channels. The coherence can be defined as the measure of synchronisation between this two brain regions in terms of spectral density. MVDR method utilises bandpass filters which are both frequency and data dependent [9]. Furthermore it has been successfully applied in this past studies [10] & [11].

II. Experiment

Continuous EEG data was simultaneously recorded with fMRI acquisition, using the MR-compatible BrainAmp-MR EEG amplifier (Brain Products, Munich, Germany) and the BrainCap electrode cap with sintered Ag/AgCl ring electrodes providing 30 EEG channels, 1 ECG channel, and 1 EOG channel (Falk Minow Services, Herrsching-Breitbrunn, Germany). The reference electrode was between Fz and Cz. Raw EEG was sampled at 5 kHz and recorded using the Brain Vision Recorder software (Brain Products).

1. RMIT University, School of Electrical and Computer Engineering, GPO Box 2476V, Melbourne, VIC 3001, Australia
2. Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel
3. Functional Brain Center, Wohl Institute for Advanced Imaging, Tel-Aviv Sourasky Medical Center, Tel- Aviv, Israel
4. Department of Psychology, Tel Aviv University, Tel Aviv, Israel
* Corresponding author name: Dr. Dean Cvetkovic;
Email: dean.cvetkovic@rmit.edu.au

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

The 30 healthy volunteers, aged 26-47 (mean 38±10.82), provided informed consent for this study, approved by the Tel Aviv Sourasky Medical Centre Helsinki committee. Subjects were equipped with headphones and asked by means of audio instructions to lie as still as possible with their eyes closed and not think of anything in particular. This recording lasted for 5 minutes and comprised the baseline condition. Following the baseline scan subjects were categorised into three groups and were instructed to fall asleep/meditate or remain awake for a total time of 15 minutes. In all conditions including baseline subjects were instructed to keep their eyes closed and lie as still as possible.

The analysis included the following 8 EEG channels: F3, F4, C3, C4, P3, P4, O1 and O2. EEG data underwent the same analysis steps as depicted in our previous work [12],[13]. In brief, two main artefacts were removed: first, artefacts related to the MR gradients were removed from all the EEG datasets using the FASTR algorithm implemented in FMRIB plug-in for EEGLAB, provided by the University of Oxford Centre for Functional MRI of the Brain, FMRIB; ([14] , [15]). Secondly, Cardio ballistic artefacts (QRS peaks) were also removed using the FMRIB plug-in. Following these pre-processing stages, the EEG data was bandpass filtered to 0.5-70 Hz and downsampled to 256Hz. To validate subjects' arousal level, the EEG data was examined and scored in accordance with known vigilance stages [5]. In this way we could ascertain that the drowsiness level of the participants was in accordance with their condition (i.e. high in the drowsiness condition and low in the meditation and awake conditions). Eventually, the data was segmented to 30 seconds epochs and the following estimates were computed for each epoch:

- MVDR Coherence estimates (MVDR filter length of 128 points and 800 resolution) using MATLAB's 'coherence_MVDR' function, based on MVDR algorithm by Benesty et al. [16].
- Alternative Matlab Coherence estimates (256 point Hanning window, 128 number of overlaps and 256 Hz sampling frequency) using MATLAB's 'mscohere' function, based on Welch Algorithm [8].
- DTF estimates (7680 points of data with 256 Hz sampling rate) using M. Kaminski's MMULTAR software [17].

Statistical analysis was performed between groups using the Kruskal-Wallis non parametric test. Results were considered significant at a level of 0.05. A post-hoc analysis was conducted using Wilcoxon-Mann-Whitney (WMW) test to investigate the significance between conditions with a Bonferroni corrected significant value *alpha*. Corrected *alpha* value was calculated by dividing 0.05 significance value by the number of comparisons being made ((# of frequency bands) x (# of electrode pair combinations)). The corrected (p) values are therefore:

Coherence: *alpha* = 0.05/(3x7x28) = 0.000085
DTF: *alpha* = 0.05/(3x7x56) = 0.0000426

III. Theory

A. Directed Transfer Function (DTF)

DTF is defined by the following equation:

$$\eta_{ij}^2(f) = \frac{\left|H_{ij}(f)\right|^2}{\sum_{k=1}^{n}\left|H_{ik}(f)\right|^2} \quad (1)$$

where $H_{ij}(f)$ is an element of matrix and input channels k=1,...,n.

The transfer function ($H(f)$) in equation 1 consists of information about the directionality of the brain signals and can be calculated using model coefficients. The transfer matrix is not a symmetric matrix providing the data flow from channel i to channel j is different from channel j to channel i. This directionality is a major property of the DTF when it is used for quantifying the information flow between brain regions.

B. MVDR coherence

The connectedness (coherence) of two signals can be defined as a measure of the correlation between the signals as a function of frequency components. It can be also defined in a statistical measure as the probability of two stochastic signals arising from a common originator process. In MVDR method, the filter coefficients are selected in order to minimise the variance of the output. Magnitude Squared Coherence (MSC) between input $x(n)$ and output $y(n)$ signals can be defined as:

$$\gamma_{xy}^2(u_k) = \frac{\left|S_{xy}(u_k)\right|^2}{\left|S_{xx}(u_k)\right|\left|S_{yy}(u_k)\right|} \quad (2)$$

where, u_k is a unitary matrix, S_{xy}=cross spectral dencity and S_{xx} and S_{yy} are auto spectral densities.

IV. Results

Statistical analysis was conducted using Statistical Package for Social Sciences (SPSS) software tool. Initially the histograms of all data sets were examined to investigate the shape of the distribution. Since most of the data was not normally distributed, the non-parametric Kruskal-Wallis test, with a significance of *p=0.05*, was applied instead of a parametric analysis of variance (ANOVA). The relative differences in coherence and DTF values were calculated by subtracting the baseline values from each condition values.

ΔDTF = DTF condition - DTF baseline (3)

ΔCOH = COH condition - COH baseline (4)

The statistical analysis was undertaken to compare the three conditions in terms of frequency bands (delta1, delta2, theta, alpha, sigma, beta and gamma) and all electrode pair combinations (F3F4, F3C3, F3C4, F3P3, F3P4, F3O1, F3O2, etc). Kruskal-Wallis test was used to compare more than two independent samples. We were interested in investigating the difference between conditions: meditation vs. awake, awake vs. drowsiness and meditation vs. drowsiness. Post-hoc analysis was further conducted using Wilcoxon-Mann-Whitney (WMW) test with the Bonferroni corrected significant *alpha* value.

A. DTF Results

Figure 1 shows a topographical view of relative difference in DTF, computed for each frequency band and all significant values, less than 0.005 were considered for the

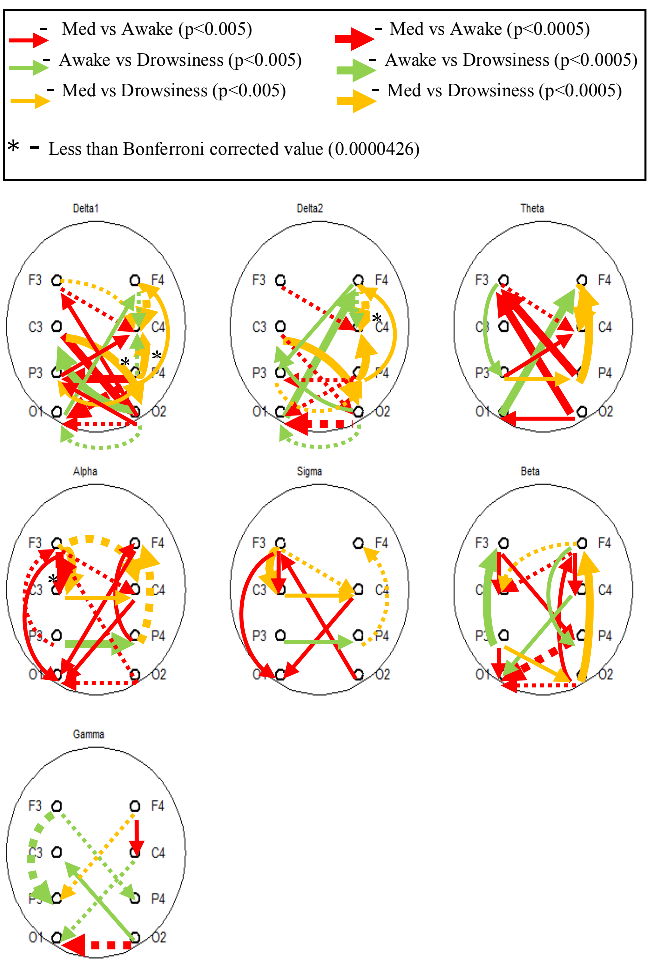

Figure 1. Summary of DTF results in a topographical pattern. The solid lines indicate a relative increase of connectedness strength and broken lines indicate a relative decrease of connectedness strength.

topographic representation. The results revealed four connections that were significantly modulated across the different conditions (*p<0.0000426*, Bonferroni corrected).

In delta1 band there was a significant increase in relative DTF from C3 to O2 in meditation compared to drowsiness conditions (U=16.814, *p<0.00004*, ME=0.018, SD=0.079). U is the sum of ranks, ME is mean and SD is standard deviation. Additionally, delta1 coupling also revealed significant increase from P4 to C4 region in meditation compared to drowsiness conditions (U=19.843, *p<0.000008*∗, ME=0.0160, SD=0.162).

In delta2 band, a significant decrease of relative DTF in meditation compared to drowsiness was also found from F4 to C4 (U=17.096, *p<0.000035*, ME=-0.005, SD=0.132). In higher frequency bands (alpha, sigma and beta) there was a relative increase of DTF from frontal electrodes to central and occipital electrodes in meditating compared to awake subjects.

In the alpha band, a significant increase was found in the coupling between F3 to C3 in the meditation compared to awake conditions (U=16.908, *p<0.000039*, ME=0.016, SD=0.066). An increase in higher frequency bands (alpha and sigma) compared to lower frequency bands (delta1, delta2 and theta) was found in the coupling between P4 to F4 in meditation compared to drowsiness conditions. A decline in alpha band and an increase in lower frequencies is a known marker of reduced vigilance [5] evident for the drowsiness condition.

These results revealed significant differences in coupling in several frontal and central locations in the meditation condition as compared to either awake or drowsiness conditions. This trend was particularly evident in alpha and sigma bands.

B. Coherence Results

Figure 2 shows a topographical view of relative differences in MVDR coherences for each frequency band. As there were no significant differences that survived the extremely low Bonferroni's corrected *alpha* (*p<0.000085*), the topographic representation also includes significant results with an uncorrected *p<0.05*.

Despite a lack of *p* corrected significant findings, the results portrayed in Figure 2 still revealed some interesting patterns. Low frequency bands (delta1 and delta2) showed less connectivity than high frequency bands (theta, alpha, sigma and gamma) in all conditions . It was interesting to note that changes in the theta frequency band were almost solely evident in the meditation condition as reported in previous studies [18], which reported an increase in frontal and central theta activity accompanied by reduced activity (deactivation) in parietal–occipital areas.

V. CONCLUSION

In the current study we applied DTF and MVDR coherence methods on EEG data derived from different

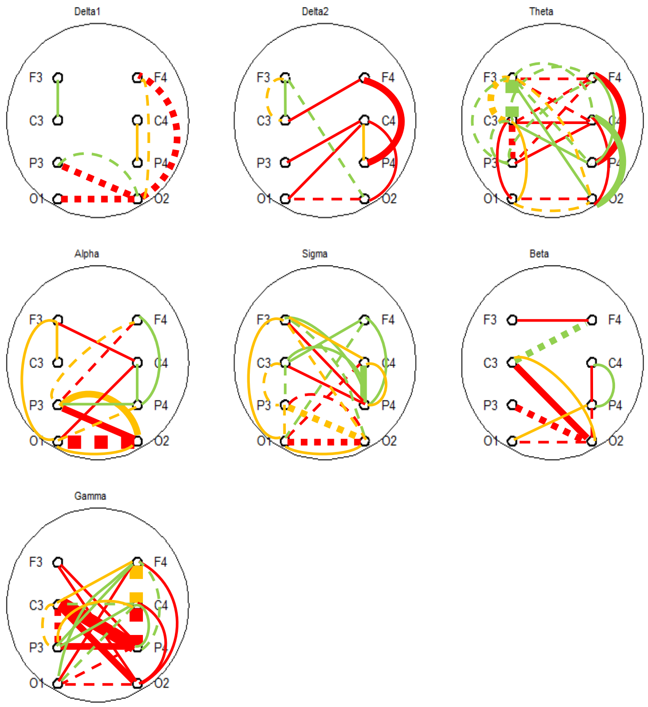

Figure 2. A summary of Coherence results in a topographical pattern. Each picture shows the significance *p* value range of the connectedness between originating and terminating electrodes. The thickness of the connections demonstrates the p value range. Solid arrows indicate an increase and broken arrows indicate a decrease in relative coherence values

attentive states: meditation, drowsiness and awake conditions. The MVDR coherence enabled the investigation of connectedness of several brain regions and DTF was used in order to examine the flow of information between these regions.

Our findings indicated significantly altered coupling patterns across different attentive conditions in several frequency bands. The lower frequency bands (particularly delta1 and delta2 bands) revealed significant changes in relative DTF between meditation and other conditions from C3 to O2 regions (Fig 1). In higher frequency bands (particularly in alpha, sigma and beta) there was a significant difference between meditating and awake subjects with regards to the relative increase of DTF from frontal electrodes to central and occipital electrodes (Fig 1). However small change was found in relative coherence results possibly due to an extremely low alpha value related to a large number of comparisons ($p<0.0000426$).

To conclude, our findings showed that both DTF and MVDR coherence could be used to get a clear estimate of the brain's information flow. In our study DTF showed superiority in terms of distinguishing the statistical differences between meditation, drowsiness and awake conditions. These signal processing methods could be used to detect and monitor subtle changes in brain activity that could also prove vital for early diagnosis of impairments in brain connectivity patterns. Specifically, the future addition of fMRI/BOLD data to our current study could enable an even better estimate of the brain's information flow and connectedness during various conditions.

REFERENCES

[1] A. K. Engel and W. Singer, "Temporal binding and the neural correlates of sensory awareness," Trends in Cognitive Sciences, vol. 5, pp. 16-25, 2001.

[2] L. M. Ward, "Synchronous neural oscillations and cognitive processes," Trends in Cognitive Sciences, vol. 7, pp. 553-559, 2003.

[3] E. Başar, C. Başar-Eroglu, S. Karakaş, and M. Schürmann, "Gamma, alpha, delta, and theta oscillations govern cognitive processes," International Journal of Psychophysiology, vol. 39, pp. 241-248, 2001.

[4] M. H. Kryger, Roth, T., William C Dement, Principles and Practice of Sleep Medicine Elsevier Limited, Oxford, 2010.

[5] S. Olbrich, C. Mulert, S. Karch, M. Trenner, G. Leicht, O. Pogarell, et al., "EEG-vigilance and BOLD effect during simultaneous EEG/fMRI measurement," NeuroImage, vol. 45, pp. 319-332, 2009.

[6] M. Kaminski and K. Blinowska, "A new method of the description of the information flow in the brain structures," Biological Cybernetics, vol. 65, pp. 203-210, 1991.

[7] P. J. Franaszczuk, K. J. Blinowska, and M. Kowalczyk, "The application of parametric multichannel spectral estimates in the study of electrical brain activity," Biological Cybernetics, vol. 51, pp. 239-247, 1985.

[8] P. Welch, "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," Audio and Electroacoustics, IEEE Transactions on, vol. 15, pp. 70-73, 1967.

[9] J. Capon, "High-resolution frequency-wavenumber spectrum analysis," Proceedings of the IEEE, vol. 57, pp. 1408-1418, 1969.

[10] D. Cvetkovic and I. Cosic, "Sleep onset estimator: Evaluation of parameters," in Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conf*erence of the IEEE*, 2008, pp. 3860-3863.

[11] D. Cvetkovic and I. Cosic, "EEG inter/intra-hemispheric coherence and asymmetric responses to visual stimulations," *Medical and Biological Engineering and Computing,* vol. 47, pp. 1023-1034, 2009.

[12] E. Ben-Simon, I. Podlipsky, A. Arieli, A. Zhdanov, and T. Hendler, "Never Resting Brain: Simultaneous Representation of Two Alpha Related Processes in Humans," *PLoS ONE,* vol. 3, p. e3984, 2008.

[13] E. Ben-Simon, I. Podlipsky, H. Okon-Singer, M. Gruberger, D. Cvetkovic, N. Intrator, *et al.*, "The dark side of the alpha rhythm: fMRI evidence for induced alpha modulation during complete darkness," *European Journal of Neuroscience,* vol. 37, pp. 795-803, 2013.

[14] I. Christov, "Real time electrocardiogram QRS detection using combined adaptive threshold," *BioMedical Engineering OnLine,* vol. 3, p. 28, 2004.

[15] K. Kim, H. Yoon, and H. Park, "Improved ballistocardiac artifact removal from the electroencephalogram recored in FMRI," *J Neourosience Methods,* vol. 135, pp. 193–203, 2004.

[16] J. Benesty, C. Jingdong, and H. Yiteng, "A generalized MVDR spectrum," *Signal Processing Letters, IEEE,* vol. 12, pp. 827-830, 2005.

[17] M. Kaminski. (Sep 10, 2011). *DTF calculations package in Matlab*. Available: http://eeg.pl/Members/maciek/MMultar

[18] S. Baijal and N. Srinivasan, "Theta activity and meditative states: spectral changes during concentrative meditation," *Cognitive Processing,* vol. 11, pp. 31-38, 2010/02/01 2010.