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ANALYSIS OF TIME-VARYING SYNCHRONIZATION OF MULTI-CHANNEL EEG SIGNALS USING WAVELET COHERENCE

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ABSTRACT

This paper proposes a novel method based on the time-frequency coherent representation for quantifying synchronization of multi-channel signals with high resolution. The presented wavelet-coherent technique provides the information regarding both the degree of coherence and the relation of phase difference. The wavelet coherence enables to provide the synchronization and the direction of information flow between two-channel signals. In addition, real EEG recordings are collected based on the cognitive targets during sentences identification and the wavelet coherence is employed for the analysis of the multi-channel EEG signals. It is observed from both the magnitude spectra and phase of the wavelet coherence that there are obvious differences between two kinds of cognitive activities. Finally, some results are illustrated with both simulation and real EEG time series to show the effectiveness of the method.

1. INTRODUCTION

The multi-channel signal processing has become a very important topic in many areas such as speech, biomedical signal analysis and communications. For example, the study of neural synchronization of multi-channel EEG signals can help us to understand the underlying cognitive processes. When some task of learning is going on, cognitive processes take place in different brain regions. Investigating neural synchronization can help us to understand the underlying cognitive processes. Conventional coherence analysis, as a linear method, employed the correlation for analysing the synchronization between two channel EEG signals. Some results have shown that the coherence of EEG recorded from different sites is usually closely correlated with cognitive processes [1-5]. However, as the changes of the physiological states and the relative environment when the cognitive and information processing take place, the statistical properties of EEG usually change with time. Many practical EEG signals turn out to be extremely non-stationary processes. The routine coherence analysis based on the assumption of stationarity fail to deal with the time-varying signals since most conventional cross-correlation methods lack the temporal resolution for the non-stationary EEG [6], which limits the dynamic synchrony analysis of practical EEG signals.

For this purpose, this paper proposes a modern time-frequency method, which provides time-varying coherent analysis via continuous wavelet transform. This novel method combines the wavelet transform with the coherence analysis, which employs an alternative way for quantifying synchronization of the signals with both temporal and spectral resolution. Wavelet coherent spectrum is defined and computed from the EEG data set such that the cross wavelet magnitude spectra serves to indicate the degree of coherence and the cross wavelet phase can be used to provide the direction of information flow between two channel signals on different cortical regions. The wavelet coherent analysis can explore the amount of synchrony among multiple-channel signals, and are used to investigate the synchronization and the corresponding information processing of the EEG signals. The simulation and some real EEG data analysis under specified cognitive task are also demonstrated.

2. TIME-VARYING COHERENCE

Morlet wavelet is chosen to provide both magnitude and phase information between two signals. The wavelet transform of the signal $x(t)$ is defined as

$$W_x(\tau,a)=|a|^{1/2}\int x(t)\psi\left(\frac{t-\tau}{a}\right)dt \qquad (1)$$

The cross wavelet spectra is define as

$$W_{ij}(\tau,a)=W_i(\tau,a)W_j^*(\tau,a)=|W_{ij}(\tau,a)|\phi(\tau,a) \quad (2)$$

The cross wavelet magnitude spectra $|X_{ij}(\tau,a)|$ reveals the degree of coherence between two signals while the phase relationship $\phi_{ij}(\tau,a)$ represents the direction of information flow between the two channels.

As a simulation, two test processes with 1000 ms length were generated for testing the behaviour of the proposed time-frequency coherence method:

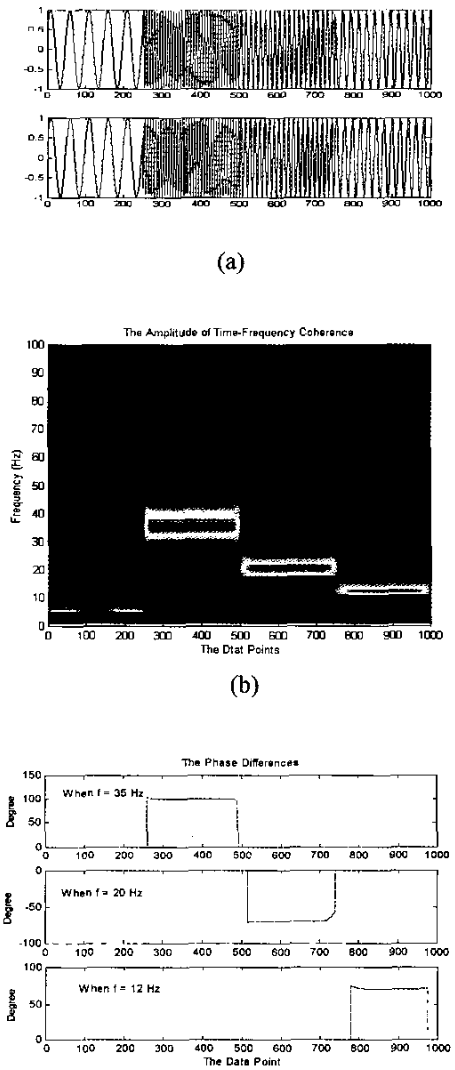
$$x_1(t)=\begin{cases}\sin(10\pi t+30\pi/180) & for \quad 0\le t<250ms\\ \sin(70\pi t) & for \quad 250\le t<500ms\\ \sin(40\pi t-70\pi/180) & for \quad 500\le t<750ms\\ \sin(24\pi t+100\pi/180) & for \quad 750\le t<1000ms\end{cases}$$

$$x_2(t)=\begin{cases}\sin(10\pi t+30\pi/180) & for \quad 0\le t<250ms\\ \sin(70\pi t-100\pi/180) & for \quad 250\le t<500ms\\ \sin(40\pi t) & for \quad 500\le t<750ms\\ \sin(24\pi t+30\pi/180) & for \quad 750\le t<1000ms\end{cases}$$

As shown in Fig.1 (a), two non-stationary test signals having 4 segments with the same frequency in each segment, but the distinguishing phase difference in segments 2, 3 and 4. The corresponding wavelet coherence is demonstrated in the Fig.1 (b) and the phase difference for segments 2, 3 and 4 was illustrated in Fig.1(c).

3. EXPERIMENTAL RESULTS

Real EEG data with 64 channels are collected based on a cognitive target of identifying a sentence in both English and Chinese from a group of Chinese students. EEGs were recorded with the 128-channel Geodesic EEG / ERP system with the sampling frequency of 250Hz. The EEG data were collected based on a cognitive target detection experiment to demonstrate the difference between the identification of Chinese and English sentence. Subjects were presented with visual stimulus of Chinese or English sentence.



(c)

Fig. 1 (a) Two channel time-varying signals having 4 segments in totally 1000 ms with different phase difference in segments 2, 3 and 4. The mono-frequency is 5Hz in segment 1, 35 Hz in segment 2, 20 Hz in segment 3 and 12 Hz in segment 4. (b) The time-frequency coherence with frequency from range 1Hz to 100 Hz. The time-varying coherent structures of the underlying signals were clearly identified. (c) From top to bottom: the phase differences for segment 2, 3 and 4 were indicated.

It is observed from the time-frequency coherence that there are obviously differences before and after identifying both Chinese and English sentences. The sentence stimulus duration was 25ms, and then 26-250ms was the identification duration. Subjects were requested to give a reaction (as press a button) when the grammar of the sentence was identified as true or false. Our interest was focused on the synchrony with the front-right regions of the brain. The channel 3 was selected as a reference point. Fig.2 (a) provides the time-varying coherence BEAM of the wavelet coherence distribution of 64 channel EEGs during performing a cognitive task before and after justifying a Chinese sentence, while the Fig. 2 (b) shows the time-varying coherence BEAM before and after justifying an English sentence. Different regions of the brain have different degree of the coherence and the information exchange patterns during processing the identification of a sentence.

Based on the preliminary analysis, there exists a significant difference between first period (1-25ms) and the second period (26-150ms) for processing the identification of both English and Chinese sentences. A lot of information exchanges take place during the period of "sentence justification". Also it can be seen that the region of information exchange when performing the Chinese sentence identification is on the middle of the brain, whereas the significant region of information exchange during English sentence justification is on the heel of the brain. The results also indicate that the EEG signals recorded at one particular site may have been originated from different sources not directly beneath the skull surface at which the electrode is located. The wavelet-based time-frequency coherent analysis between EEG signals from different sites provides us a new way to effectively track the changing procedure of the coherence and extract the useful information of EEG signals on how a learning process is in action. The proposed approach also proves the effectiveness and applicability for other non-stationary physical signals.

4. CONCLUSION

A time-frequency coherence analysis, wavelet coherence, of non-stationary signals is proposed for investigating the time-varying synchrony between different channel signals. Morlet wavelet is applied on the coherent analysis of multi-channel signals. Wavelet coherence is defined which enables us to investigate the synchronization and the information flow during processing the cognitive task of justifying sentences in Chinese and English among the brain regions in the specified cognitive tasks of identifying sentences in Chinese and English using both the wavelet coherent spectrum and the cross wavelet phase relationship. The results indicated that different regions of the brain have different degree of synchrony and information exchange patterns during processing the cognitive tasks.

5. ACKNOWLEDGEMENT

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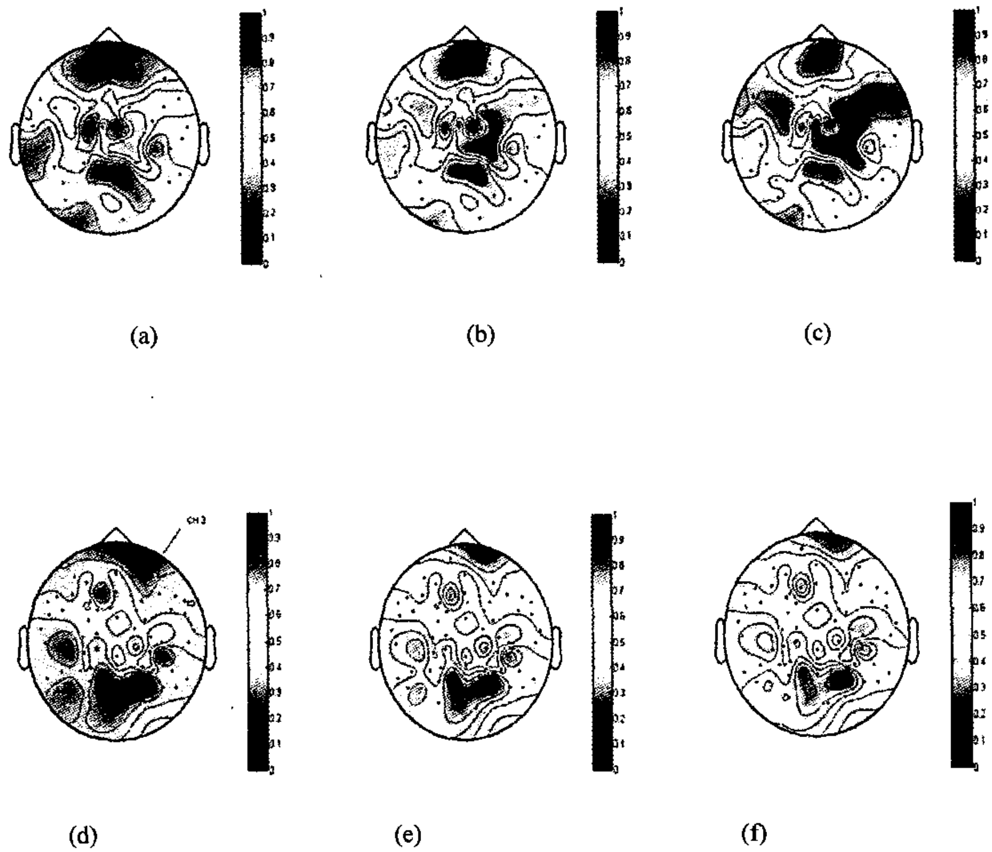

Fig.2 An example of time-varying coherence BEAM between channel 3 and other channels for 3 segmented EEGs recorded before and during justifying the sentence. The different regions of the brain have different degree of synchrony and information exchange patterns during processing the identification of both Chinese and English sentence. (a): before identifying the Chinese sentence, (b)-(c): during identifying the Chinese sentence. (d): before identifying the English sentence. (e) and (f): during identifying the English sentence.