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Time–frequency component analyser and its application to brain oscillatory activity

Ahmet Kemal Özdemir[a], Sirel Karakaş[b,c,*], Emine D. Çakmak[b,c],
D. İlhan Tüfekçi[a], Orhan Arıkan[a]

[a] Bilkent University, Department of Electrical Engineering, 06533 Bilkent, Ankara, Turkey
[b] Hacettepe University, Specialty Area of Experimental Psychology, 06532 Beytepe, Ankara, Turkey
[c] The Scientific and Technical Research Council of Turkey, Brain Dynamics Multidisciplinary Research Network, Ankara, Turkey

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Abstract

Currently, event-related potential (ERP) signals are analysed in the time domain (ERP technique) or in the frequency domain (Fourier analysis and variants). In techniques of time-domain and frequency-domain analysis (short-time Fourier transform, wavelet transform) assumptions concerning linearity, stationarity, and templates are made about the brain signals. In the time–frequency component analyser (TFCA), the assumption is that the signal has one or more components with non-overlapping supports in the time–frequency plane. In this study, the TFCA technique was applied to ERPs. TFCA determined and extracted the oscillatory components from the signal and, simultaneously, localized them in the time–frequency plane with high resolution and negligible cross-term contamination. The results obtained by means of TFCA were compared with those obtained by means of other commonly used techniques of ERP analysis, such as bilinear time–frequency distributions and wavelet analysis. It is suggested that TFCA may serve as an appropriate tool for capturing the localized ERP components in the time–frequency domain and for studying the intricate, frequency-based dynamics of the human brain.

Keywords: Event-related potentials; Oscillatory brain activity; Brain signal analysis; Time–frequency signal analysis; Component analysis; Biomedical signal processing

1. Introduction

The present paper introduces a technique of signal analysis in the time–frequency plane. The technique characterizes the oscillatory components of the complex neuroelectric responses of the brain by identifying and extracting the maximal energies of the oscillatory components and localizing them in the time–frequency plane. It simultaneously displays all significant components in the time–frequency plane and thus presents them in their entirety. The time localization of the frequency components is of high resolution and has negligible cross-term contamination. In addition, a comparison of this technique with existing techniques of time–frequency analysis used for electrical signals of the brain is presented.

The brain emits temporally-ordered electrical signals, which can be recorded from the scalp of animals or humans. These electrical fluctuations can be measured as the event-related potentials (ERPs), which are the time-domain responses to external or internal stimuli (Picton et al., 1974; Picton, 1988). The basic technique for ERP waveform analysis is averaging. This technique is used for extracting the components of the evoked ERP from the superimposed, randomly occurring noise and for increasing the signal-to-noise ratio (Dawson, 1954).

Pioneering work on the gamma and alpha oscillations inspired the study of oscillatory activity of the brain (Berger,

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[*] Corresponding author. Present address: Hacettepe University, Specialty Area of Experimental Psychology, Beytepe Campus 06532, Ankara, Turkey. Tel.: +90 312 297 8335; fax: +90 312 299 2100.

E-mail addresses: kozdemir@ieee.org (A.K. Özdemir), skarakas@hacettepe.edu.tr (S. Karakaş).

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1929; Adrian, 1942). Recently, the analysis of the oscillatory responses of the brain to external or internal stimuli, the event-related oscillations (EROs), has gained much acceptance. Another approach to brain's neuroelectricity has thus become its analysis in the frequency domain. Intensive research shows that the oscillations at various frequencies are valid indices of the brain's information processing operations (for review, see Başar, 1998, 1999; Porjesz et al., 2002; Kamarajan et al., 2004).

The time evolution of the amplitudes, i.e. the ERP waveform alone cannot provide the time localization of the frequency components. Frequency-domain analysis involves the decomposition of ERP into its constituent oscillations (for a review, see Başar, 1980, 1998). Growing amount of research shows that the compound ERP and the ERP components are determined by the superposition of oscillations, called event-related oscillations, in various frequency ranges (Başar, 1980, 1998; Başar et al., 2000; Başar and Ungan, 1973). Karakaş et al. (2000a, 2000b) have demonstrated that, for a series of cognitive paradigms, the amplitudes of the ERP components are determined by a specific combination and phase relationship of oscillatory components, specifically in the delta and theta ranges. The importance of phase relationship of multiple oscillatory components in the production of the average waveform has been demonstrated in the influential study by Makeig et al. (2002). This study showed that the average event-related potential is a combination of phase resetting of ongoing EEG activity with concurrent energy increases. It thus emphasized the importance of oscillatory components and stimulus-induced phase resetting.

One of the widely used methods for demonstrating oscillatory responses of the brain is the transient (evoked) response frequency characteristics method (TRFC). In TRFC, the amplitude–frequency characteristics are computed by the application of one-sided Fourier transform to the transient response (Solodovnikov, 1960; Parvin et al., 1980; Başar, 1980, 1998; Jervis et al., 1983; Brandt and Jansen, 1991; Röschke et al., 1995; Kolev and Yordanova, 1997). Since the amplitude–frequency characteristics are not computed by the successive application of different frequencies, rapid transitions that occur in the brain signal do not present a problem for the TRFC method. The peaks in the amplitude–frequency characteristics (AFC) reveal the resonant frequencies of the system: its excitability and also its response susceptibility (Başar, 1998; Yordanova and Kolev, 1998). The AFC graph thus demonstrates amplitude variations of frequency selectivities. However, it cannot provide the time localization of the components. The technique also assumes that the system studied is linear. Owing to these, the distinctly appearing peaks in TRFC are used in the literature to obtain only a global description of the tuning frequencies of the system (for review, see Başar, 1998, 1999).

Since the oscillatory and non-stationary signal components whose superposition form the ERP waveform are concurrently localized in both the time and frequency domains, time–frequency signal processing is the natural tool for the analysis of non-stationary signals with localized time–frequency supports. Time–frequency distributions (TFDs) are two-dimensional functions that assign the energy content of signals to points in the time–frequency plane (Cohen, 1989). The performance of a TFD is related to its accuracy in describing the signal's energy content in the time–frequency plane, keeping spurious terms negligible. Composite (multi-component) signals, such as biological, acoustic, seismic, speech, radar and sonar signals, whose components have compact time–frequency supports form an important application area for time–frequency signal analysis (Cohen, 1995).

A widely used approximation to time–frequency representation of brain signals is digital filtering (DF). In this method, independent filters are consecutively applied to ERP. Filter limits in DF may be obtained in a response-adaptive way such that the low and high cut-off frequencies of the filters are determined from the frequency range of the resonant selectivities in the corresponding AFC (Cook III and Miller, 1992; Farwell et al., 1993; Başar, 1980). DF thus produces oscillatory components of varying amplitudes within the empirically or theoretically determined filter limits. DF is not well suited to discern the time evolution of an oscillation in a given frequency range in the time–frequency domain.

Another commonly used technique is the wavelet analysis (WA) (Samar et al., 1999). This time–frequency approach is a technique that decomposes the signal into a set of basis functions, called wavelets. If the components of ERP can be represented by using distinct wavelet basis components, then the wavelet decomposition is successful on the desired ERP. When different sizes of wavelets are used, WA may provide a better time-scale localization than DF. Results obtained by WA thus depend on the chosen wavelet prototype. Quadratic B-spline wavelet and orthogonal cubic spline wavelet have proved useful in demonstrating the frequency components in ERP signals (Başar, 1998; Demiralp et al., 1998, 1999, 2001; Başar et al., 1999; Yordonova et al., 2002). Other approaches such as continuous wavelet transform with matching pursuits and wavelet packet models use multiple wavelet prototypes that are selected from a predefined set. The modifications by Rosso et al. (2001) have made it possible to calculate the wavelet entropy and the relative wavelet energy of the different frequency components. Thus, WA provides the time localization of the frequency components. The efficiency of the localization, however, depends on the suitability of the chosen wavelet basis to the complex and highly non-stationary ERPs.

Short-time Fourier transform (STFT) may be a natural choice when analysing the time–frequency characteristics of the ERP signal (Cohen, 1989). However, STFT fails to resolve those ERP components that are closely localized in the time–frequency plane. To increase the resolution of the ERP components in the time–frequency plane, the Wigner distribution can be used (Cohen, 1989). The Wigner distribution