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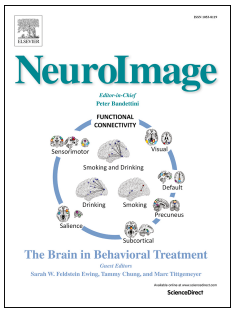

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The Bispectrum and Its Relationship to Phase-Amplitude Coupling

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Abstract

Most biological signals are non-Gaussian, reflecting their origins in highly nonlinear physiological systems. A versatile set of techniques for studying non-Gaussian signals relies on the spectral representations of higher moments, known as polyspectra, which describe forms of cross-frequency dependence that do not arise in time-invariant Gaussian signals. The most commonly used of these employ the bispectrum. Recently, other measures of cross-frequency dependence have drawn interest in EEG literature, in particular those which address phase-amplitude coupling (PAC). Here we demonstrate a close relationship between the bispectrum and popular measures of PAC, which we relate to smoothings of the signal bispectrum, making them fundamentally bispectral estimators. Viewed this way, however, conventional PAC measures exhibit some unfavorable qualities, including poor bias properties, lack of correct symmetry and artificial constraints on the spectral range and resolution of the estimate. Moreover, information obscured by smoothing in measures of PAC, but preserved in standard bispectral estimators, may be critical for distinguishing nested oscillations from transient signal features and other non-oscillatory causes of "spurious" PAC. We propose guidelines for gauging the nature and origin of cross-frequency coupling with bispectral statistics. Beyond clarifying the relationship between PAC and the bispectrum, the present work lays out a general framework for the interpretation of the bispectrum, which extends to other higher-order spectra. In particular, this framework holds promise for the detailed identification of signal features related to cross-frequency coupling and transient phenomena. We conclude with a discussion of some broader theoretical implications of this framework and highlight promising directions for future development.

Keywords: EEG, ECoG, Higher-order statistics, Polyspectra, Point process, Blind deconvolution

1. Introduction

Many interesting properties of signals in nature relate to nonlinear, non-Gaussian and non-stationary dynamics, which are poorly indexed by second-order measures such as power and cross spectra. Because the spectrum of a stationary Gaussian process lacks any statistical dependence across frequencies, measures of frequency-domain dependence can be extremely useful for gauging the presence and nature of higher order dynamics [51]. For stationary signals, higher order spectra, "polyspectra," which capture such dependence, are the frequency-domain representations of higher

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