MEASURES OF LINEAR AND NONLINEAR INTERDEPENDENCE OF ELECTROCORTIGRAM TIME SERIES FROM EVOKED-RESPONSE POTENTIAL EXPERIMENTS


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ABSTRACT

In this brief discussion, we consider various coupling measures applied to electrocortigram (ECoG) data. The analysis consists of both linear and nonlinear measures of coupling — or interdependence — between two ensembles of measurements collected at two electrodes in an evoked-response potential (ERP) experiment. The interdependence measures are applied to simulated time series data and experimental ECoG data. The algorithms discussed here are implemented in the Interactive Data Language (IDL) and available for download from the authors.

1. INTRODUCTION

The analysis of electrocortigram (ECoG) time series data provides important tools for understanding the functioning of the human neocortex. The poor signal-to-noise ratio in most ECoG recordings is often overcome by performing an evoked-response potential (ERP) experiment. In ERP experiments, the stimulus is presented to the subject many times under nearly identical conditions. These repeated, nearly identical experiments give rise to an ensemble of measurements, which then require analysis. In this brief discussion we implement traditional linear (Sec. 2) and recently developed nonlinear (Sec. 3) measures suitable for analysis of an ensemble of measurements. These measures are computed using the Interactive Data Language (IDL) and are available from the authors. The measures are applied to simulated time series in Sec. 4 and ECoG time series collected from a human subject in Sec. 5.

2. LINEAR MEASURES

Linear measures are well known and often utilized in the analysis of ECoG time series. In what follows, we compute the cross correlation coefficient [1], the coherence [2], and the event-related coherence [3] for an ensemble of repeated measurements. The results of these measures applied to simulated and experimental data are presented below.

3. NONLINEAR MEASURES

Recently, nonlinear measures of coupling — or interdependence — between ECoG time series have become more popular. Following the physics literature, we refer to these measures of nonlinear interdependence as synchronization measures. Many synchronization measures have been developed, including identical synchronization [4], generalized synchronization [5], phase synchronization [6], and synchronization techniques robust to noisy data [7] [8]. Applications of these measures to ECoG time series data can be found in, among others, [9] [10] [11]. Below we will use a measure of synchronization described in [9]. For this measure, the synchronization results are computed for each trial in the ensemble of measurements then averaged over the ensemble in the obvious way.

Recently a new synchronization measure has been proposed specifically for the analysis of an ensemble of repeated measurements collected in an ERP experiment [12]. The main assumption of this measure is that the response of the neocortex will trace approximately the same trajectory in each repeated experiment. The interested reader may consult [12]. This new synchronization measure is especially suited to an ensemble of short time series consisting of oscillatory bursts of activity, as commonly found in many ERP experiments.
4. SIMULATED EXAMPLE

We applied the three linear measures mentioned in Sec. 2 and the two nonlinear measures mentioned in Sec. 3 to simulated data. The simulated data were computed from the non-identical coupled Henon map discussed in [8]. For analysis purposes we chose the sampling interval $dt$ to be 1 s. An ensemble, consisting of 40 trials each 300 points in duration, was computed for the system of Henon maps. The two maps in this system were strongly coupled only during the middle portion of each trial (100 s to 150 s); otherwise, the two maps were not coupled. We show the results of the linear measures applied to these two ensembles of simulated data in Fig. 1. We show the results of the nonlinear measures in Fig. 2.

5. EXPERIMENTAL DATA

In this section, we apply the three linear measures mentioned in Sec. 2 and the two nonlinear measures mentioned in Sec. 3 to electrocortical (ECoG) data collected during an ERP experiment. The ECoG data were recorded from an awake patient undergoing neurosurgery for tumor removal and done in accordance with UCSF human subjects requirements. Seven ball electrodes were placed near the known position of primary and secondary auditory cortices. Two epidural electrodes served as reference and ground for the differential amplifiers. The analog signals were bandpass filtered between 0.1 and 250 Hz, amplified by $10^4$, and digitized at a sampling rate of 2003 Hz with 16 bit resolution. The data were subsequently high-pass filtered above 2.3 Hz using using a symmetrical finite response filter and all epochs with detectable artifact were removed.

In the analysis discussed here, the stimuli of the ERP experiment consisted of short duration (180 ms) tones occurring at a single frequency at a rate of 0.5 Hz. For a detailed description of the traditional ECoG methods and results, see [13]. Here we apply the linear and nonlinear measures of interdependence to an ensemble of measurements collected at two of the ball electrodes. The results of the linear measures are shown in Fig. 3 and the results of the nonlinear measures are shown in Fig. 4.

6. DISCUSSION

Many linear and nonlinear analysis tools are available for investigating the interdependence of two ensembles of ECoG data collected in an ERP experiment. The linear measures are well-known and computationally fast. The nonlinear measures are still somewhat esoteric, computationally expensive, and lack a rigorous statistical method for computing the error of the measure.

The tools mentioned in this discussion have been implemented in the Interactive Data Language (IDL) and are available from the authors. We also note the valuable resource [14] for analysis tools written in Matlab.

7. REFERENCES


Fig. 1. Linear interdependence measures applied to the unidirectionally coupled non-identical Henon map. Here the index $n$ and the time $t$ are equivalent because the sampling time $dt = 1.0$. (a) Upper: The cross correlation coefficient shows an increase near zero lag but does not reveal the change in coupling strength between 100 s and 150 s. Lower: The coherence function shows coherence between the ensembles at frequencies greater than 0.1 Hz but does not reveal the change in coupling strength. (b) The event-related coherence. Values between 0.0 and 1.0 follow a linear grayscale from white to black. The event-related coherence suggests the ensembles are coherent during the interval 100 s to 150 s.

Fig. 2. Synchronization measures applied to the unidirectionally coupled non-identical Henon map. Here the index $n$ and the time $t$ are equivalent because the sampling time $dt = 1.0$. (a) The synchronization measure $N(x[n]|y)$ from [9], smoothed over a window of size 11 at each time point, increases during the interval of nonlinear coupling ($100 < n < 150$) between the two ensembles. (b) The synchronization measure $T(x[n,\eta]|y)$ from [12] smoothed over a two-dimensional window of size 11 at each time point. Note that the axes show time along the ensembles. In the contour plot, there are five evenly spaced contour levels, ranging from 0.0 (white) to 0.08 (black). The diagonal line in the figure corresponds to the location of zero time lag. See [12] for details. The contour plot shows synchronization occurs during the time interval $100 < n < 150$. 
Fig. 3. Linear interdependence measures applied to the ensembles of measurements collected at two electrodes during an ECoG ERP experiment. The analysis considered times 120 ms preceding the stimulus presentation to 220 ms following the stimulus presentation. (a) Upper: The cross correlation coefficient shows a strong linear coupling between the ensembles of measurements at zero time lag. Lower: The coherence function shows coherence between the two ensembles of measurements over a broad frequency range. (b) The event-related coherence. Values between $0$ and $1$ follow a linear grayscale from white to black. The event-related coherence suggests the two ensembles are coherent at frequencies ranging from 0 Hz to 40 Hz between 50 ms to 120 ms following the stimulus presentation.

Fig. 4. The synchronization measures applied to two ensembles of measurements collected by two electrodes from an ECoG ERP experiment. The analysis considered times 120 ms preceding stimulus presentation to 220 ms following stimulus presentation. (a) The synchronization measure $N(x[n]y)$ from [9] smoothed over a window of size 11 at each time point. This measure increases slightly above its pre-stimulus value between 50 ms and 100 ms following the stimulus presentation. (b) The synchronization measure $T(x[n, \eta]y)$ from [12] smoothed over a two-dimensional window of size 11 at each time point. The solid diagonal line corresponds to the location of zero time lag. The horizontal and vertical dashed lines correspond to the time of stimulus onset. $A$ and $B$ designate the two electrodes under consideration. For this figure there are 10 evenly spaced contour levels from 0.01 (white) to 0.19 (black). Note the region of synchronization from 40 ms $< n < 130$ ms in $A$ and 70 ms $< n < 110$ ms in $B$. 