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Detection of nonlinear event-related potentials

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Abstract

The methods used to evaluate event-related potentials (ERPs) are generally insensitive to nonlinear responses. Our goal was to show that nonlinear ERPs could be detected using recurrence analysis (RA). When fixed-phase sine signals were added to baseline electroencephalograms (EEGs), the added linear determinism was detected by signal averaging, as expected, and by RA. However, when nonlinear determinism was simulated by adding either random-phase sine or Lorenz signals, the added signals were detected only by RA. Auditory evoked potentials (AEPs) were studied in five subjects using RA. We detected not only the characteristic linear effects caused by onset and offset of the sound, but also nonlinear AEPs not previously reported; they occurred at 473–661 ms after onset, and 282–602 ms after offset, depending on the subject. In five other subjects we found nonlinear magnetosensory evoked potentials; they occurred at 209–354 ms after field onset, depending on the subject. RA was less sensitive than time averaging for detecting linear ERPs, but had the advantage of being able to detect nonlinear ERPs.

Keywords: Event-related potentials; Nonlinear method; Auditory evoked potentials; Magnetosensory evoked potentials; Recurrence analysis; Time averaging; Magnetic field

1. Introduction

An event-related potential (ERP) is a change in the electrical state of the brain that occurs in response to a discrete sensory or cognitive event (Lopes da Silva, 1999). The change may arise from the addition of a signal to the electroencephalogram (EEG) (Ruchkin, 1988), or from processes that do not satisfy the principle of superposition such as stimulus-induced phase resetting of ongoing EEG rhythms (David et al., 2005; Graben and Frisch, 2004; Makeig et al., 2002; Penny et al., 2002). Whatever its origin, an ERP is always detected simultaneously with the totality of ongoing brain electrical activity and with signals due to eye movement, muscle activity, and nonbiological noise.

An ERP that arises by superposition on the baseline EEG can be extracted by averaging away the portion of the signal that is not time-locked to the stimulus onset. It has long been recognized, however, that the variability rejected by the averaging process might itself be physiologically significant (Regan, 1975). The presence of nonlinear determinism in the EEG (dynamic changes governed by nonlinear differential equations) has been studied using Lyapunov exponents and fractal dimension (Stam, 2005), but neither method has been shown to be useful for detecting ERPs, perhaps because the methods require a stationary signal, which is a condition often not realized in practice. Presently, there are no established methods for verifying the presence of nonlinear event-related potentials.

In the absence of a priori knowledge regarding how an ERP is generated, the optimal detection procedure is one that makes minimal assumptions regarding the dynamical nature or statistical properties of the recorded signal, but yet affords a requisite sensitivity. Our purpose was to describe recurrence analysis (RA), a method that meets these conditions and appears to be particularly useful for detecting nonlinear ERPs. First, we describe the mathematical and statistical steps involved in using RA for detecting ERPs. Then, a mathematical model of ERPs created by adding segments of linear or nonlinear waveforms to baseline EEG signals is used to compare the ability of RA and time averaging to detect the added signals. Third, we apply RA to auditory

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evoked potentials and show that, in addition to the expected linear responses, nonlinear responses that were not detected by means of signal averaging also occurred after both onset and offset of the sound. Finally, we present another example that indicates RA reveals the occurrence of nonlinear evoked responses, namely the occurrence of magnetosensory evoked potentials.

2. Materials and methods

2.1. EEG measurements

EEGs were recorded from O_1, O_2, C_3, and C_4 referenced to linked ears (International 10–20 system) using gold-plated electrodes attached to the scalp with conductive paste; the subjects were clinically normal. The signals were amplified using a multichannel recording system (Nihon Kohden, Irvine, CA) filtered to pass 0.5–35 Hz, sampled at 10 kHz (to accurately characterize signal amplitude) and stored on a computer hard-drive.

A sound stimulus consisting of a binaural 454 Hz tone (10 ms rise and fall times) was presented to each of five subjects; the sound pressure at the location of the subject was 65 dB. A subliminal magnetic field stimulus was applied to five additional subjects. Uniaxial magnetic fields, 2 G, 60 Hz, uniform to within 5% in the region of the head, were applied in the coronal plane by means of two sets of three coplanar, coaxial coils; the coil sets were separated by 65 cm. Each set consisted of a circular coil (21 turns, radius of 21.6 cm), and two square coils (85, 120 turns, respective side length of 48.3 and 66 cm). The coil current was obtained using a function generator (Model 182A, Wavetek, San Diego, CA) and amplifier (Model 7500, Krohn-Hite, Avon, MA), and was applied by means of a zero-crossing switch controlled by a computer-generated timing signal.

The stimuli were applied for 2 s, with a 5 s inter-stimulus period (7 s trial); at least 80 trials were recorded for each subject. Trials that contained visible artifacts were discarded and the artifact-free trials were sub-sampled at 300 Hz (because the original 10 kHz rate proved unnecessary for the RA calculations), digitally filtered between 0.5 and 35 Hz, and then analyzed by RA and time averaging.

The Institutional Review Board at the LSU Health Sciences Center approved all procedures involving human subjects.

2.2. Modeling

A nonlinear event-related potential is defined here as a stimulus–response relationship in which the response is manifested in the EEG and is governed by nonlinear differential equations. Assessment regarding whether an EEG contains evidence of nonlinearity is made by determining whether the putative response (1) has zero mean and (2) can be detected by recurrence analysis. If the answer to both questions is yes, then the event-related potential is considered to be nonlinear.

To mimic determinism occurring in the EEG in response to a sensory stimulus, 300 ms segments of fully deterministic signals were added to baseline EEG trials. The added signals had an RMS value equal to that of the epochs to which they were added. Three model signals were considered: (1) a 10 Hz sine wave that had a constant phase; (2) a 10 Hz sine wave whose phase varied randomly from trial to trial; and (3) a portion of a solution of the nonlinear system of Lorenz equations (Abarbanel, 1996; Lorenz, 1963); the parameters were chosen so that the system was in the chaotic domain. The augmented trials were analyzed using both RA and time averaging to assess their relative ability to reveal the added signals.

2.3. Recurrence analysis

Recurrence analysis was developed by Webber and Zbilut to detect deterministic behavior in time series data, such as the EEG. The deterministic behavior may be linear or nonlinear; RA imposes no constraints on the stationarity or statistical characteristics of the time series (Webber and Zbilut, 1994).

Use of RA to detect actual or simulated event-related potentials involves phase space embedding of successive intervals of the EEG signal, calculation of the corresponding recurrence plots, and quantification of the plots using an appropriate nonlinear quantifier (Fig. 1). The time series of the quantifier is computed for each of a sufficient number of independent epochs, and the ERP is detected by time averaging or, if necessary, statistical comparison with the time series of the quantifier computed from control epochs.

The mathematical details of RA have been described elsewhere (Eckmann et al., 1987; Takens, 1981; Webber and Zbilut, 1994; Zbilut and Webber, 1992). Briefly, the method is based on the principle that the occurrence of deterministic changes in the EEG caused by a sensory or cognitive stimulus can be identified by analyzing the composite signal together with a number of time-lagged versions of the signal (Takens, 1981). After choosing an embedding dimension (M) and a time delay (τ), the brain's electrical activity is represented by a series of M-dimensional vectors, the sequence of which corresponds to a trajectory in the phase space. The trajectory is represented in two dimensions by a recurrence plot (Eckmann et al., 1987), which can be quantified using any of a number of nonlinear quantifiers (Webber and Zbilut, 1994; Zbilut and Webber, 1992); the quantifier used here is percent recurrence ($\%R$), defined as the ratio of the number of recurrent points to the total number of points in the recurrence matrix (Eckmann et al., 1987). Points in phase space are said to be recurrent if the distance between them in phase space is less than an adjustable parameter (here, chosen to be 15% of the maximum distance). For calculating the distances, we used the Euclidean norm (Zbilut and Webber, 1992).

A phase space can be constructed for an entire epoch of the EEG, leading to a single value of $\%R$. For example, if an EEG voltage, $V(t)$, is sampled at 300 Hz for 2 s (600 measurements) and embedded in a phase space (say, $M = 5$, $\tau = 5$), the result is a trajectory consisting of $N - \tau(M - 1) = 580$ points, from which a recurrence plot can be computed (Fig. 1a, $\%R = 15.5\%$). However, to detect the transient changes in the EEG produced by the ERPs, it was necessary to iterate the calculation, using a sliding window of points in $V(t)$ to produce a corresponding time series, $\%R(t)$; this process captured the dynamic activity (both linear and nonlinear) in the EEG occurring over small time intervals (Fig. 1b). For example, use of the first 30 points (100 ms) in $V(t)$