Nonlinear analysis of hemodynamic response in the fusiform face area

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Abstract

Number of studies postulated that the linear system analysis could characterize the hemodynamic responses of fMRI data. From that reason, most of available softwares use this for analysis of the fMRI responses. We hypothesized that all the neural activity of the human cerebral region measured by fMRI is not underlying linear system-based hemodynamic responses. In this work, we investigated the nonlinear characteristic hemodynamic response of the fusiform face area using nonlinear system identification based on Laguerre expansion techniques. The results of nonlinear analysis showed more and broader activation region compared to the linear system analysis. Further studies should be needed to clarify this.

Introduction

There is a growing appreciation of the importance of nonlinear estimation in hemodynamic responses in fMRI. These nonlinearities are commonly expressed on the relationship between neural activity and the BOLD (blood oxygenation level dependent) fMRI signal. We will present the method for the nonlinear characteristic hemodynamic response based on Laguerre expansion techniques that are used to find kernels from nonlinear system identification. The advantages of this technique are: 1) it yields rather accurate kernel estimates from short data-records, even in the presence of noise; 2) it removes the strict requirement of white-noise inputs [1][2]. All these studies are investigated on the human fusiform face area (FFA) [3].

Methods

As stimuli, total of 16 faces, 16 objects and the retinotopic stimuli (checker board with 8 Hz flickering) were chosen for the study. Each stimulus was presented for 1.5 seconds following a blank screen for 0.5 seconds and this repeated eight times within a block (ON phase). During OFF phase a fixation point was presented for 30 seconds. We had total 6 blocks per one experimental run. Images were acquired using a 3 Tesla MR scanner in KAIST (ISOL Tech., Korea). 15 slices with 3 mm thickness (no gaps) were obtained. First, the ON and OFF phase were used for linear regression analysis for BOLD signal time course. Using an empirical model of the temporal dynamics of the fMRI signal, hemodynamic predictors were computed from the ON and OFF phases, and a general linear model (GLM) was computed for every voxel. We acquired several voxels and voxel time courses that are activated by faces stimuli, namely the human fusiform face area (FFA). Second, we focused on the nonlinear system identification. The nonlinear system is driven by an input, $u(n)$, and produces an output signal, $y(n)$. The input consists of the ON (1) and OFF (0) phases that correspond to the ON and OFF phases of faces stimuli, respectively. The output is the voxel time courses that are activated only by face stimuli. And some zeros are added to both the ON (1) and OFF (0) phases of input and the first voxel time course of output (Fig. 1). We will assume that the system can be represented by a finite Volterra series (1).

$$y(n) = k_0 + \sum_m k_1(m)u(n-m) + \sum_{m_1}\sum_{m_2} k_2(m_1,m_2)u(n-m_1)u(n-m_2) + \cdots \qquad (1)$$

Expansion of the Volterra kernels on the Laguerre basis $\{h_i(m)\}$ transforms (1) into the multinomial power series express as follows,

$$y(n) = c_0 + \sum_{i=1}^{L} c_1(i)x_i(n) + \sum_{i=1}^{L}\sum_{j=1}^{i} c_2(i,j)x_i(n)x_j(n) + \cdots \quad (2) \quad \text{where} \quad x_i(n) = \sum_m h_i(m)u(n-m) \quad (3)$$

and $c_1(i)$ and $c_2(i,j)$ represent the Laguerre expansion coefficients of the 1st- and 2nd-order kernels, respectively. The unknown expansion coefficients can be estimated in practice by linear regression of the output data $y(n)$ on the terms of the multinomial expansion of (2), as long as it is finite. The terms of the multinomial expansion depend on the signals $x_i(n)$ given by (3) as convolutions of the input data with the selected Laguerre discrete-time functions

$$h_i(m) = \alpha^{(m-i)/2}(1-\alpha)^{1/2}\sum_{k=0}^{i}(-1)^k \cdot \binom{m}{k}\binom{i}{k}\alpha^{i-k}(1-\alpha)^k, (m \geq 0, 0 < \alpha < 1)$$

where α is the discrete-time Laguerre parameter which determines the rate of exponential asymptotic decline of these functions. There is a straightforward relationship between the Wiener-Bose model, and the finite Volterra series. Given the coefficients, $c_1(i)$, $c_2(i,j)$, …, and the impulse responses, $h_i(m)$, the Volterra kernels can easily be generated from the Wiener-Bose model[1][2]. As a result, we have earned the first three Volterra kernels, k_o, k_1, k_2.

Results

The acquired 1st- and 2nd order kernel for the fusiform face area (FFA) are shown in Fig. 2. The trend of 1st order kernel is analogous with the general hemodynamic response modeled by Gamma function. For example, the 1st order kernel corresponds to the conventional [1st order] hemodynamic response function and shows the characteristic peak at about 4 seconds. The results of analysis using the acquired 1st and 2nd order kernel for detecting the fusiform face area (FFA) shows that both statistic value and size of effect are larger than the result of analysis using the conventional [1st order] hemodynamic response function in case of uncorrected p-value of 0.001 (Fig. 3). In case of corrected p-value 0.05, the detection of fusiform face area (FFA) is only represented when the acquired 1st and 2nd order kernels are used.

Discussion

In order to analyze fMRI data, we have used Laguerre expansion technique for the analysis of the fMRI hemodynamic response. And we earned better detection of the fusiform face area compared to the results of using conventional hemodynamic response (Fig. 3). We would speculate that the relationship between neural activity and the BOLD (blood oxygenation level dependent) fMRI signal is nonlinear. Future studies are the investiagation of the empirical hemodynamic responses of the fusiform face area (FFA) using event-related experiment.

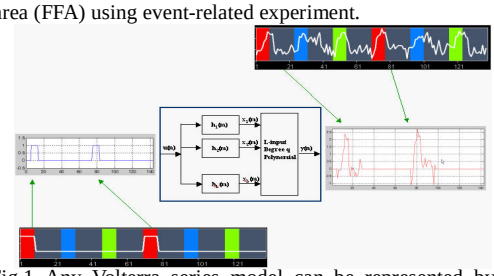

Fig.1 Any Volterra series model can be represented by a Wiener-Bose model, consisting of a bank of linear filters whose outputs are combined and transformed by a multiple-input polynomial. In general, the impulse response functions (IRFs) of the L filters in the filter bank, $h_i(t)$ $1 \leq i \leq L$, are chosen prior to the identification.

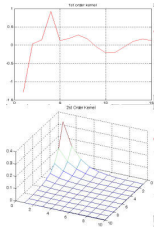

Fig. 2 The first and second order Volterra kernels based on Laguerre expansion technique from a voxel in FFA.

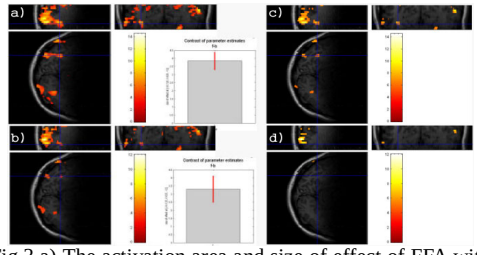

Fig.3 a) The activation area and size of effect of FFA with estimated 1st and 2nd kernel using Laguerre expansion technique, uncorrected p< 0.001. b) Same description as a) with conventional hemodynamic response. c) The detection of FFA with estimated using Laguerre expansion technique, corrected p< 0.05. d) Like c) with conventional hemodynamic response.

References

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