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Adaptive Kalman filtering for real-time mapping of the visual field

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ABSTRACT

This paper demonstrates the feasibility of real-time mapping of the visual field for clinical applications. Specifically, three aspects of this problem were considered: (1) experimental design, (2) statistical analysis, and (3) display of results.

Proper experimental design is essential to achieving a successful outcome, particularly for real-time applications. A random-block experimental design was shown to have less sensitivity to measurement noise, as well as greater robustness to error in modeling of the hemodynamic impulse response function (IRF) and greater flexibility than common alternatives. In addition, random encoding of the visual field allows for the detection of voxels that are responsive to multiple, not necessarily contiguous, regions of the visual field.

Due to its recursive nature, the Kalman filter is ideally suited for real-time statistical analysis of visual field mapping data. An important feature of the Kalman filter is that it can be used for nonstationary time series analysis. The capability of the Kalman filter to adapt, in real time, to abrupt changes in the baseline arising from subject motion inside the scanner and other external system disturbances is important for the success of clinical applications.

The clinician needs real-time information to evaluate the success or failure of the imaging run and to decide whether to extend, modify, or terminate the run. Accordingly, the analytical software provides real-time displays of (1) brain activation maps for each stimulus segment, (2) voxel-wise spatial tuning profiles, (3) time plots of the variability of response parameters, and (4) time plots of activated volume.

Introduction

Although functional MRI (fMRI) has a long history of scientific applications in neuroscience, translating this research into clinical applications has lagged considerably. In order to make a successful transition from research lab to medical clinic, fundamental changes are required in: (1) experimental design, (2) statistical analysis, and (3) display of results.

Many clinical (as well as research) applications require experimental paradigms having multiple, simultaneous test conditions. An important example of this requirement is mapping of the visual field, where visual activation corresponding to multiple radial wedge locations, multiple concentric rings, etc., must be mapped onto the visual cortex. Therefore, any real-time algorithm must be capable of analyzing multiple simultaneous test conditions and allow the possibility that individual voxels may be responsive to multiple conditions, such as multiple visual field locations. Indeed, some voxels may be responsive to noncontiguous visual field locations (e.g., voxels straddling a sulcus), which further complicates the modeling process..

Proper experimental design is essential to achieving a successful outcome, particularly for real-time applications. We show that a random-block experimental design has less sensitivity to measurement noise, as well as greater robustness to error in modeling of the hemodynamic impulse response function (IRF) and greater flexibility than common alternatives. In addition, random encoding of the visual field allows for the detection of voxels that are responsive to multiple, not necessarily contiguous, regions of the visual field.

Due to the sequential nature of image acquisition and the large quantity of data, numerical calculations should be performed recursively for real-time display of results. That is, new data should be processed as it is acquired without the need to reprocess all of the previously acquired data. Also, to correct for subject motion, magnetic field perturbations, changes in subject's attention, etc., it is necessary to use statistical methods that can adapt to spurious signal perturbations, in real time, on a voxel-by-voxel basis. Due to its recursive nature, the Kalman filter is ideally suited for real-time statistical analysis of visual field mapping data. An important feature of the Kalman filter

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is that it can be used for nonstationary time series analysis. The capability of the Kalman filter to adapt, in real time, to abrupt changes in the baseline arising from subject motion inside the scanner and other external system disturbances is important for the success of clinical applications.

For clinical applications, it is desirable that brain images, functional activation maps, and statistical results be displayed in real time, so that the clinician can decide when sufficient data have been collected, if it is necessary to extend or to repeat the imaging run, or to change the parameters of the experiment itself Accordingly, the methodology described here provides real-time displays (updated approximately once per volume acquisition) of (1) brain activation maps for each stimulus segment, (2) voxel-wise spatial tuning profiles, (3) time plots of the variability of response parameters, and (4) time plots of activated volume.

Nonstationary time series analysis

A critical challenge for real-time analysis of fMRI data, and a major cause of data loss in clinical applications, is the *nonstationarity* of the data (i.e., the statistics of the random processes vary over time). Changes over time in the statistics of the time series may arise due to subject motion, variation in measurement noise level, "spikes" in the data, magnetic field distortions, change in subject attention level, slow changes in the vascular hemodynamic response due to physiological or neuronal processes, etc. Conventional fMRI time series analysis methods, such as cross-correlation, multiple regression, deconvolution, etc., assume that the underlying stochastic processes are stationary. Although attempts have been made to model temporally correlated error, such as using the auto-regressive moving average (ARMA) model, such models also assume that the time series are stationary (Chatfield, 2004; Shumway, 1988). An alternative method, the Kalman filter, is a powerful tool for analysis of *nonstationary* time series (Bozic, 1979; Gelb, 1974; Grewal and Andrews, 2001; Zarchan and Musoff, 2005). Furthermore, since the Kalman filter is a recursive algorithm, it has been successfully used in a wide variety of real-time applications. In this paper, we present an implementation of the adaptive Kalman filter tailored specifically for analysis of nonstationary fMRI time series data.

In order to illustrate the Kalman filter method, we present results from two fMRI visual field mapping experiments, which were conducted using random visual field excitation paradigms. For the first experiment, the visual field was mapped in one dimension using angular sectors (wedges). In the second experiment, the visual field was mapped in two dimensions (angle and eccentricity) simultaneously using radial sectors. Kalman filtering was implemented for simultaneous multiparameter estimation of the visual field response profile for each voxel of interest. In addition, real-time mapping of the visual field was simulated, post-experiment, along with a real-time graphical display of the visual field map. This was then used to explore optimization of the simulated scan duration, so that the run length is just sufficient to obtain statistically reliable activation maps. These experiments, and subsequent real-time simulations, demonstrated the feasibility of using Kalman filtering for real-time analysis and interpretation of the results from a visual field mapping paradigm for clinical applications.

A recurring theme of this paper is that it is advantageous to think of the fMRI imaging run not as a monolithic, *static* entity, but rather as an ongoing, *dynamic* process. From this point of view, run length is not a fixed constant but a variable, depending on the time required to achieve the desired parameter estimation accuracy. This has implications for the experimental design, data analysis methods and assumptions, and the graphical user interface, as explained below.

Application to visual field mapping

A conventional approach for fMRI mapping of the visual field uses a visual stimulus consisting of a rotating pie wedge or a set of expanding rings, each made up of an 8 Hz, flashing, black and white checkerboard pattern extending to 20° eccentricity. Typically, this method has been referred to as "temporal phase encoding" of the visual field. This is illustrated by the top row of Fig. 1, which shows the visual stimulus over 6 of 20 epochs separated by intervals of 2 s. In contrast, for "random-block encoding", a particular region of the visual field, whether a "wedge" or a "ring", is "ON" for fixed-length blocks of time, but these blocks are randomly placed within the allotted run time. This is illustrated by the bottom row of Fig. 1 for narrow wedge segments.

It is informative to consider the time sequence representation, or "stimulus functions", for these respective designs. A stimulus function is a binary sequence that indicates the times when a particular stimulus location is "ON". For phase encoding of the visual field, the stimulus function for a particular wedge (or ring) location is a periodic function of time. This is illustrated in Fig. 2(a), which displays the time sequence of activations for each wedge location.

(Note: In this and some of the following illustrations, we have used particular color codings for different "segments" within the visual field, as indicated by the color wheel in Fig. 2. This is for illustrative purposes only, to help the reader in distinguishing and identifying different regions within the visual field. We reiterate that the subject in the scanner saw only a flashing, black and white checkerboard display, as illustrated in Fig. 1.)

From Fig. 2(a), we see that these stimulus functions are periodic, and more importantly, the stimulus functions for neighboring wedges are temporally phase shifted relative to each other. Therefore, a voxel is mapped to a single location in the visual field based on the time delay (or phase shift) of the measured fMRI time series relative to the input reference waveforms. Note, in particular, the similarity of the stimulus functions corresponding to neighboring wedge locations. This observation applies not only to the rotating hemi-field design but also to the expanding ring paradigm, as well as "moving bar" experiments (Dumoulin and Wandell, 2008). Although the "moving bar" paradigm does not use phase encoding, it is still the case that nearby locations in the visual field are activated by temporally similar stimulus functions.

One alternative to the phase encoding method is to use a randomized design. Typically, analysis of a randomized design is based on the assumption of system linearity (see, e.g., Boynton et al., 1996; Dale and Buckner, 1997). Here, we follow up on our previous work using a randomized design for fMRI mapping of the visual field (Ward et al., 2006). An important feature of the random-block encoding method is that stimulus functions corresponding to neighboring wedges are linearly independent. This is illustrated in Fig. 2(b). Note that this contrasts with the phase encoding method in which stimulus functions corresponding to neighboring wedges are related by a small, constant phase shift.

The advantages of the random-block encoding method, relative to the phase encoding method, are:

- Greater noise immunity. Since the reference waveforms for the phase encoding method are not as distinct as the random-block encoding waveforms, it is easier for measurement noise to make the response to one input stimulus sequence look like the response to another.
- The phase encoding method is more susceptible to modeling errors due to temporal variability, from voxel to voxel, in the hemodynamic response. Variability in the hemodynamic response has less effect on the random-block encoding method, which uses random code sequences, not time delay, for identifying the voxel visual field response.
- The phase encoding method is usually limited to a single "answer" for each voxel, due to the "winner-take-all" nature of the analysis that is typically used. That is, each voxel is identified as responding to a particular point location within the visual field. This method