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Wavelet coherence of EEG signals for a visual oddball task

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ABSTRACT

Neural co-activation in frontal and central cortex was examined during a visual oddball task using wavelet coherence. EEG was recorded during a visual oddball task, presented to 12 participants with a random mix of 15% oddball targets and 85% frequent non-target letters over 265 trials. Wavelet coherence of individual trials was shown to distinguish frequent and oddball trials. Averaged wavelet coherence showed significant differences: oddball targets showed higher delta–theta activity whereas frequent background stimuli showed higher gamma activity. Increased gamma coherence appeared to be related to expectation of the targets with our analysis showing an R^2 of 0.935 for the relationship between averaged sections of gamma coherence and the number of intervening (frequent) trials since the last oddball.

Contents

1. Introduction

The typical frequency range of electroencephalogram (EEG) signals is from 0.5 to 100 Hz with an amplitude of less than 100 μV; the amplitude is heavily affected by the mental activity of the participant. This range has been divided into five EEG bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz) and gamma (>30 Hz) [1]. Whereas much of the EEG signal occurs spontaneously, a subset can be related to provocation from external stimulus sources. These are referred to as event related potentials (ERPs) [2]. An ERP waveform may arise from either features of the stimulus (exogenous) or from higher-order processing of the stimulus (endogenous). It may also arise by time locking the EEG to response events, to reveal motor potentials. A widely used task for reliably producing an endogenously generated ERP is the oddball detection task. This involves the occasional presentation (e.g., 15%) of a target stimulus, for example the character 'X', amidst a stream of background or frequent (standard) stimuli, such as the character 'O'. That task

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reliably produces the "P300" to the targets, i.e., a positive potential between 250 and 500 ms post-stimulus that is maximal at midline parietal and central locations.

Some studies include a third stimulus as a "deviant" which does not have a response requirement but does impact on the EEG. The present investigation (and review here) used the simple two-stimulus paradigm.

In a recent review of the theory of the P300, Polich [3] noted that the context updating account has been most versatile and resistant to refutation. The context updating account states that the P300 arises during brain activity "underlying revision of the mental representation induced by incoming stimuli." For the oddball task, on most of the trials the irrelevant stimulus category is processed and its response executed. Occasionally this context changes (oddball presented) and a shift in mental context is required to generate the correct response. The task relies on a working memory for recent events and attention-related processes [3]. Moreover, it has been used extensively in the study of attention-deficit disorder [4].

The aim of the present investigation was to show that individual oddball trials can be examined with a wavelet coherence technique and to gain insight into the neural connectivity used during task performance by using multi-trial analysis. Moreover, the following sections review related studies of the visual oddball tasks and some of their neural correlates. Furthermore, the wavelet transform is described and its application to bio-signal processing introduced along with gamma band activity, in order to provide the necessary background for the present investigations.

In [5] the researchers used a visual oddball target detection task and fMRI brain imaging. They found that the random infrequent targets activated the middle frontal gyrus (MFG) of the dorso-lateral pre-frontal cortex (dPFC). In an fMRI study [6], the authors compared frontal cortex activation by non-relevant novel stimuli and relevant oddball targets (each presented on 4% of trials, with standards presented on 92% trials). They showed that while targets activated MFG of the frontal lobe, novel stimuli did not. While in [7] the authors note that the detection of targets in an oddball task reliably activates pre-frontal cortex, their fMRI study showed that this occurs as part of the response strategy (to shift to an alternative response from the frequently occurring standards) as opposed to simply generating a response. Furthermore, they assert that the PFC is associated with "context-dependent control of behavior" and responds in a modality-free fashion [8]. In a review of studies incorporating several recording methodologies, Linden concluded that processing the novelty of an oddball P300 involves activation of frontal cortical areas [2]. In addition, target detection has been reliably shown to activate the parietal and temporal cortices. Polich [3] noted that an easy oddball discrimination task (like that used in the present study), results in a P300 arising over central–parietal sites and that novelty tends to show activation on more anterior sites [3]. Hence, the Cz electrode site should be an effective choice to monitor oddball P300 activity. Furthermore, Polich [3] noted that the brain imaging investigations support the conclusion of the presence of a "circuit pathway between frontal and temporal/parietal brain areas". While brain imaging studies as summarized above provide a basis for identifying areas of activation during the visual oddball task, a different method of analysis is needed to provide some evidence for connectivity by a "circuit-pathway". Coherence between two electrodes is superior to comparison of amplitudes when the goal is to examine possible pathways of communications between two brain sites, particularly at gamma frequencies [9,10]. Wavelet coherence is a recent method for analyzing coherence of brain activity between two electrodes [11].

The wavelet transform (WT) has been an important tool for feature extraction in analyzing non-stationary time series (e.g., specifying the high power regions in the time–frequency plane from these signals) [12,13], The continuous wavelet transform (CWT), which provides coefficients at all scales (and thus permits fine frequency discrimination at the cost of redundancy), has been extensively used for signal analysis including non-stationary signals such as EEGs [11]. Wavelet analysis, generally, represents the signal in the time–frequency plane and can provide the coefficients' energy distribution in the EEG time series [11]. In addition to time information, CWT can capture amplitude and phase information when a complex wavelet function is used [14]. Since synchronization of brain sites underlies cognitive processes, wavelet coherence (WC) may be a useful tool in the study of this synchronization [11] although so far, little has been published. For two examples see [15,16].

In the present study, CWT coherence analysis was used to highlight significant features between oddball and frequent single EEG trials and to examine the proposed neural circuit connectivity between the frontal and central/parietal areas.

This paper investigated both low-frequency (delta-theta) and the full spectrum of gamma activity during both the stimulus presentation and the response interval for the task. In this regard, it was hypothesized that communication between frontal decision processes and central–parietal cortex response processes would show low frequency coherence, reflecting the driving processes underlying the P300 waveforms. In addition to the P300, the oddball task has also been shown to result in gamma band activity [17]. Furthermore, Ref. [18] reports that during an oddball task the frequent standard trials evidenced increased gamma at a time (250 ms or more) just prior to the P300 response. This may reflect the observer expecting an imminent oddball. This effect was examined in this paper. It has been well established that event-related brain activity can be considerably smaller in amplitude than the background EEG yielding a poor SNR. A common means of improving the SNR of signals synchronized to an event is to present several trials of a particular stimulus (typically 20 or more) and then averaging the brain activity in the time domain. Thus, the SNR was increased in proportion to the square-root of the number of trials used in the average [19]. However, Ref. [20] argued that complex cognitions (such as monitoring for rare stimulus events in the oddball task) involve induced gamma band activity which is asynchronous relative to stimulus onset (and would therefore cancel when time-lock averaging). Therefore, they argue that the time-frequency decomposition be performed prior to averaging for resolving this gamma signal.

The remainder of this paper is organized as follows: In Section 2 the EEG data acquisition method is given along with a detailed description of the oddball test. In addition, the concepts and methods of CWT and WC are introduced. Section 3 applies wavelet analysis on the EEG data and presents significant differences between the oddball and frequent trials in spectral graphs. Finally, Section 4 provides discussion and conclusions.

2. Methods

2.1. Data acquisition

The EEG signals were recorded from a 32-electrode cap according to the 10/20 international system. Data were collected from 12 participants with an average age of 20.08 ± 2.61; 8 of them were males. The Griffith University ethics number for human research was (PSY/92/09/HREC).