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Statistical evaluation of recurrence quantification analysis applied on single trial evoked potential studies

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HIGHLIGHTS

- Recurrence quantification analysis (RQA) allows quantifying signal characteristics of single trial ERPs measured with and without noise induced by parallel MRI.
- RQA power to discriminate responses to different tone types in an oddball experiment was not significantly superior to a linear amplitude analysis.
- However, RQA has the potential to provide additional trial-by-trial information compared to classical amplitude based analysis.

ABSTRACT

Objective: We evaluated the potential of recurrence quantification analysis (RQA) to improve the analysis of trial-by-trial-variability in event-related potentials (ERPs) experiments.
Methods: We use an acoustic oddball paradigm to compare the efficiency of RQA with a linear amplitude based analysis of single trial ERPs with regard to the power to distinguish responses to different tone types. We further probed the robustness of both analyses towards structured noise induced by parallel magnetic resonance imaging (MRI).
Results: RQA provided robust discrimination of responses to different tone types, even when EEG data were contaminated by structured noise. Yet, its power to discriminate responses to different tone types was not significantly superior to a linear amplitude analysis. RQA measures were only moderately correlated with EEG amplitudes, suggesting that RQA may extract additional information from single trial responses not detected by amplitude evaluation.
Conclusions: RQA allows quantifying signal characteristics of single trial ERPs measured with and without noise induced by parallel MRI. RQA power to discriminate responses to different tone types was similar to linear amplitude based analysis.
Significance: RQA has the potential to detect differences of signal features in response to a standard oddball paradigm and provide additional trial-by-trial information compared to classical amplitude based analysis.

1. Introduction

Evoked potentials in response to external stimuli are low in amplitude compared with the electroencephalographic (EEG) background signal. Therefore, in most studies on event-related potentials (ERPs), the EEG is averaged over several trials to remove EEG background activity that is usually considered non-informative, and to increase the signal-to-noise ratio (SNR). In this approach, it is an intrinsic assumption that the electrophysiological response to a stimulus of the same physical characteristics remains stable over the experiment, i.e. is stationary. However, in neuropsychological experiments, responses to single stimuli are variable over time, with a wide range of modulating factors such as fluctuating attention, habituation and other psychological processes that are triggered by repeated stimulus presentation (Acharya et al., 2005; Crowley and Colrain, 2004; Polich, 2007; Mander et al., 2008; Ruby et al., 2008). Averaging across trials may therefore obscure potentially meaningful trial-by-trial variance that reflects true variation of the cerebral response. This may affect e.g. simultaneous ERP and functional magnetic resonance imaging (fMRI) analyses, in which correlation of each single ERP with its

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corresponding fMRI volume is required. Therefore, particularly for event-related fMRI analysis, methods are sought that allow for a robust quantification of the electrophysiological response to a single trial.

Several research groups have reported advanced methods to detect minute changes in the EEG response to a single trial. Benar et al. (2007) were able to track changes of the P300 response throughout an EEG-fMRI oddball experiment after filtering the EEG data. Similarly, independent component analysis (ICA) and wavelet based denoising have been proposed to improve single trial characterization (Iyer and Zouridakis, 2007; Debener et al., 2005; Zouridakis et al., 2007; Bagshaw and Warbrick, 2007; Mantini et al., 2009). Either approach has its specific advantages and limitations, and so far, no standard method for single trial analysis has been established (Mutihac and Mutihac, 2007).

In this study we probed the potential of Recurrence Quantification Analysis (RQA) to improve the characterization of single trial EEG responses. RQA is a non-linear signal analysis method originally proposed by Zbilut and Webber (1992) that does not require any specific assumptions about the statistical properties of the data. Generally, RQA quantifies different aspects of regularity in the data. In contrast to other non-linear analysis methods, RQA can also be applied to relatively short non-stationary time series (Marwan, 2003). Carrubba et al. (2007a,b, 2008) compared the classical method of temporal averaging against RQA to detect magnetic evoked responses, and reported that these responses were better detected by RQA. Schinkel et al. (2009) investigated the EEG response in a semantic mismatch paradigm that typically evokes a N400 deflection. They compared the sensitivity of linear amplitude analysis with RQA on a trial-by-trial level and demonstrated that RQA was more sensitive in detecting semantic mismatch. Marwan and Meinke (2004) employed RQA to analyse single trial responses in a proof-of-concept study using an acoustic oddball paradigm and demonstrated that RQA may differentiate responses to frequent and rare tones. However, no group analyses or statistical test comparing RQA against linear amplitude analysis were presented. A further aspect not investigated for RQA so far is its robustness towards MR induced artefacts, caused by the static magnetic field and by rapidly switching magnetic field gradients, which make the combination of single trial EEG with functional MRI very challenging.

The main goal of this study was to compare RQA that extracts non-linear signal features with more conventionally used linear amplitude analysis (LA) of single trial responses. Here, we focussed on the power of the respective method to distinguish responses to different types of stimuli in an acoustic oddball paradigm. Second, we probed to which degree either method would be robust to MR induced artefacts. For this purpose we performed EEG and combined EEG-fMRI measurements in a group of healthy volunteers during an acoustic oddball paradigm.

The oddball experiment has been long used to probe orienting responses and deviance detection. Basically, the experiment comprises the presentation of a series of tones in which frequent tones (presented at one pitch) are interspersed with rarely occurring tones (Ref. to as rare tones, presented at a different pitch). Such an experiment typically elicits the ERP components N100, P200 and P300. The P300 deflection has been extensively discussed in the literature and is thought to represent an electrophysiological signature of aspects of attention, novelty detection and memory updating processes (e.g. Dalbokova et al., 1990; Polich et al., 1997; Ma et al., 2008). The average P300 amplitude is inversely proportional to the proportion of rare tones, i.e. the frequency of appearance of rare tones (Dalbokova et al., 1990; Polich, 2007). The N100 and P200 deflections are related to perceptual processing and are dependent on the individual's attention level (Rosburg et al., 2008; Mulert et al., 2008). N100 and P200 are further reflecting physical tone features like pitch and loudness (Crowley and Colrain, 2004).

Given the huge body of acquired knowledge on the electrophysiological signatures of evoked potentials in an oddball experiment, this experiment was chosen to test performance of RQA. Several systematic analysis steps were performed: First, a suitable RQA measure was selected from a set of candidate measures and EEG channel locations in a conservative fashion to reduce the subsequent number of analyses. We then compared RQA measures with linear ones with respect to their potential to distinguish responses to frequent and rare tones. Next, we compared these measures with respect to their power to distinguish responses to frequent tones positioned before and after a rare tone, as the appearance of a rare tone may change the context of the experimental background, e.g. by arousing the subject. Last, in order to prepare for combined EEG-fMRI experiments, we investigated the robustness of both methods towards additional MRI induced noise in the raw data.

2. Methods

2.1. Subjects

Eleven right-handed healthy subjects (7 men, 4 women; mean age 27.8 ± 2.8 years) were recruited by public advertisement. They underwent a diagnostic interview to exclude any current general medical, neurological or psychiatric condition, and to exclude any general contraindication for MRI. The study protocol followed the guidelines of the Declaration of Helsinki and was approved by the local ethical committee. All participants gave their written informed consent and were paid for their participation. All of them performed an active oddball task outside and inside the MR scanner on the same day. Data of two subjects were excluded due to strong movement artefacts, leaving nine subjects for final analysis.

2.2. Experimental task

Subjects performed an active acoustic oddball paradigm (Zenker and Barajas, 1999; Lindin et al., 2004; Barry et al., 2007) in both sessions. Presentation software (Neurobehavioral Systems, Albany, USA) was used for task programming and stimulus delivery. The oddball task consisted of the presentation of two types of tones: Rare tones (1.4 kHz, duration 100 ms including 10 ms rise and fall times) and frequent tones (1 kHz, duration 100 ms including 10 ms rise and fall times), the latter ones considered as acoustic background pattern. The order of the tones was randomly assigned with two consecutive rare tones always being separated by at least two frequent tones. The overall frequency of appearance was 90% for frequent and 10% for rare tones. This distribution criterion had to be fulfilled for subsets of 20 tones. The inter-stimulus interval was 1 s with jittering of ±250 ms. The experiment consisted of a total of 600 tones presented over 15 min and was performed both outside and inside the MRI scanner. Tone stimuli were presented via headphones, and subjects wore ear plugs as a safety requirement during MR measurements. All subjects participated in an MR test session to become acquainted to the MR environment prior to the actual experiment. To adjust loudness of the acoustic stimuli, a preparation scan was performed during which subjects had to repeatedly decide whether or not they perceived the tones as loud as the fMRI scanner sound. This resulted in a defined level of subjectively identical loudness of tones and scanner noise. For the final experiment, tones were delivered 3 dB louder for better perception (within an absolute range of 80–85 dB). Subjects were instructed to keep the eyes open in order to reduce EEG alpha activity, which otherwise would lead to strong background EEG signal, and to press a button with their right index finger as fast