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Shapeless Adaptive Removal of the Transcranial Alternating Current Stimulation Artifact from the Electroencephalogram

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April 19, 2017

Abstract

Your abstract.

1 Introduction

The combination of transcranial alternating current stimulation (tACS) and electroencephalogram (EEG) has been explored in several recent studies. While the analysis of EEG before or after stimulation posits limited technical challenges, the EEG recording during stimulation is heavily affected by the stimulation artifact.

1.1 Matched Phase and Frequency

Computational simulations suggest that the power of endogenous oscillations would increase most if the frequency of tACS matches the targets eigenfrequency (Kutchko and Fröhlich, 2013; Zaehle et al., 2010). This has been supported by evidence from animal studies (Schmidt et al., 2014), and human studies combining tACS with transcranial magnetic stimulation (TMS) (Guerra et al., 2016), or contrasting pre and post resting state power analysis (Zaehle et al., 2010). It has also been suggested that the phase of neuronal populations would be locked to the phase of the tACS signal (Reato et al., 2013). This has been supported by evidence from studies combining tACS with motor output (Brittain et al., 2013), TMS (Raco et al., 2016; Nakazono et al., 2016) or sensory perception (Gundlach et al., 2016).

This suggests that the effect of tACS can result in neurophysiological effects which are phase-and frequency-matched to the stimulation artifact. Such frequency and phase matching between tACS and EEG recordings can render the removal of the artifact difficult or impossible, as the signal might no longer be separatable from the artifact.

1.2 Non-Stationary Amplitude Modulation

An approach to tackle this issue is to assess the time-course of the EEG signal. Consider the assumption that the artifact is stationary and superpositioned on the physiological signal. Then, modulations in the amplitude of the recorded EEG-signal must be caused by changes in the underlying physiology. This would be the case, even if frequency and phase are matched to the stimulation signal. Approaches assuming such stationarity of the stimulation artifact have been used e.g. by Pogosyan et al. (2009).

Yet, detailed analysis of the stimulation artifact provides evidence that the artifact amplitude is actually not stationary. Instead, the amplitude is modulated by heart-beat and respiration (Noury et al., 2016). Consider furthermore that event-related responses like modulation of skin impedance can also affect the scalp conductance at stimulation electrodes. This would introduce event-related amplitude modulation of the

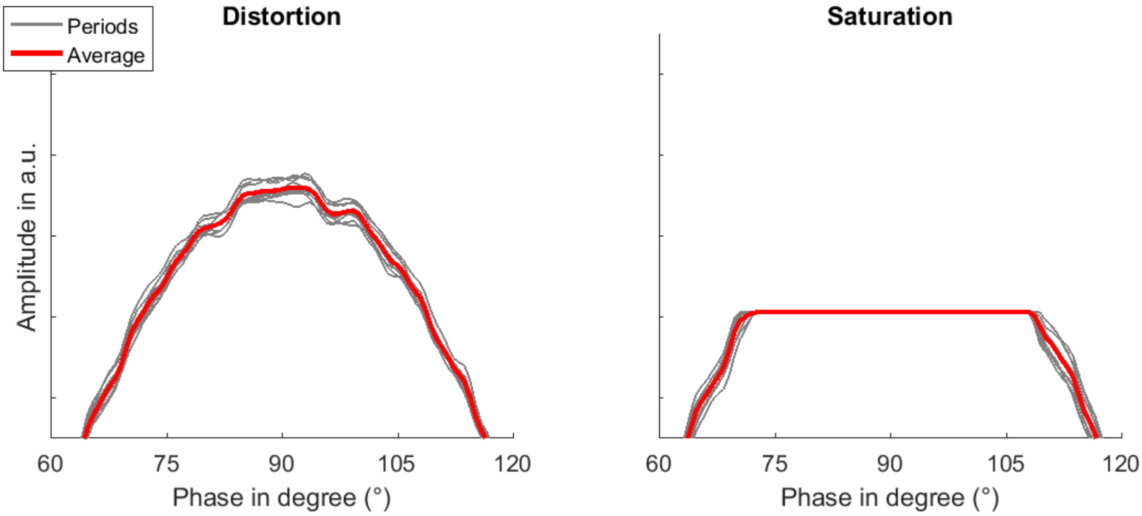

Figure 1: Non-Sinusoidality
It shows the distortion/saturation of the sinus waveform using two exemplary trials of tACS-EEG. The gray traces indicate nine invididual periods, while the red trace indicates their average. In the left figure, noe the periodic, but non-sinusoidal waveform. In the right figure, note the saturation.

stimulation artifact. In that regard, disentangling true signal from the stimulation artifact stays technically challenging.

1.3 Artifact Distortion

Ideally, the stimulation artifect resembles a sinusoid. Yet, practical experience suggests that the signal is usually distorted to various degrees. (see figure 1).

A major reason for distortion by amplifier saturation, i.e. the stimulation artifact exhibits an amplitude to large for the dynamic range of the amplifier, causing the signal to be cut off. Even when close to the saturation threshold, non-linearites in the amplifier slew rate can distort the shape. Additionally, the temporally and spatially uneven impedance distribution has been suggested to cause distortion, rendering the resulting waveform periodic, but non-sinusoidal.

1.4 Computational Demands

Methods based on adaptive template construction and temporal principal component analysis (tPCA) (Niazy et al., 2005) have been explored for removal of non-stationary and misshaped tACS artifacts (Helfrich et al., 2014). Consider that the process of template construction, the estimation of accurate weights for initial removal and the removal of residual artifacts using tPCA artifact removal is computationally cumbersome, and often requires off-line analysis supported by visual inspection. This multi-staged template-approach has therefore of limited utility for on-line artifact removal. Furthermore, a critical evaluation has suggested that the residual artifact spans several principal components, and a sufficient artifact removal is not possible with tPCA (Noury et al., 2016).

1.5 Rationale

We were interested in development of a computationally fast approach, feasible for online artifact removal. At the same time, the approach was required to account for the non-stationarity of the artifacts amplitude, and the possibility of non-sinusoidal distortion and saturation. Ideally, the approach should allow to estimate physiological signals at the frequency of stimulation, even if physiological oscillations were phase-locked to the stimulation signal.

2 Approach

The main idea is that at any given time point t, the recorded signal $r(t)$ is a linear superposition of a neurophysiological signal $n(t)$, the stimulation artifact $a(t)$ and a white noise term $e(t)$. The task is to recover $n(t)$ by estimating $a(t)$ and $e(t)$ and subtracting from $r(t)$.

$$r(t) = n(t) + a(t) + e(t) \tag{1}$$
$$n(t) = r(t) - a(t) - e(t) \tag{2}$$

2.1 Artifact Estimation

Assume that the tACS artifact were *non-sinusoidal*, but *stationary and periodic*, while any neurophysiological signals n were absent. We could estimate the amplitude of a at any time-point t by using the recorded signal r from any tACS one period length τ_a earlier (4).

$$r(t) = a(t) + e(t) \tag{3}$$
$$\hat{a}(t) \sim r(t - \tau_a) \tag{4}$$
$$\hat{a}(t) \approx \sum_{n=1}^{N} \frac{r(t - (n\, \tau_a))}{N} \tag{5}$$

Because the white noise term e is superpositioned on r, and because $\langle e \rangle$ converges asymptotically to zero with increased sample size, an aproach optimal to achieve an unbiased estimate of the amplitude of a stationary artifact would be to average across as many earlier periods as possible (5). Subsequently, this estimate can be used to remove the artifact from r.

2.2 Scaling

$$\hat{a}(t) \approx \sum_{n=1}^{N} w_n r(t - (n\, \tau_a)) \tag{6}$$

Practice of linearization of dynamical systems -> linear decrease with n by using the triangular number T_N

$$T_N = \frac{N(N+1)}{2} \tag{7}$$
$$w_n = \frac{N - n + 1}{T_N} \tag{8}$$
$$= \frac{2(N - n + 1)}{N(N+1)} \tag{9}$$

and the physiological signal exhibit different time-constants we can estimate

Consider that the modulation of the

highly similar amplitude at any given time-point as during earlier periods plus a white noise term. We can scale how far back the

convolution with a kernel removing any signal with the same period length as the tACS artifact. Depending on the number of periods,

3 Evaluation

4 Conclusion

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