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EEG phase reset due to auditory attention: an inverse time-scale approach

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Abstract

We propose a novel tool to evaluate the electroencephalograph (EEG) phase reset due to auditory attention by utilizing an inverse analysis of the instantaneous phase for the first time. EEGs were acquired through auditory attention experiments with a maximum entropy stimulation paradigm. We examined single sweeps of auditory late response (ALR) with the complex continuous wavelet transform. The phase in the frequency band that is associated with auditory attention (6–10 Hz, termed as theta–alpha border) was reset to the mean phase of the averaged EEGs. The inverse transform was applied to reconstruct the phase-modified signal. We found significant enhancement of the N100 wave in the reconstructed signal. Analysis of the phase noise shows the effects of phase jittering on the generation of the N100 wave implying that a preferred phase is necessary to generate the event-related potential (ERP). Power spectrum analysis shows a remarkable increase of evoked power but little change of total power after stabilizing the phase of EEGs. Furthermore, by resetting the phase only at the theta border of no attention data to the mean phase of attention data yields a result that resembles attention data. These results show strong connections between EEGs and ERP, in particular, we suggest that the presentation of an auditory stimulus triggers the phase reset process at the theta–alpha border which leads to the emergence of the N100 wave. It is concluded that our study reinforces other studies on the importance of the EEG in ERP genesis.

Keywords: EEG phase reset, auditory attention, inverse transform, time–scale, wavelet phase stability

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1. Introduction

Event-related potentials (ERPs) are normally considered as the time-locked, stimulus-locked and synchronized activity of a group of neurons that add to the background electroencephalograph (EEG). On the other hand, the evoked responses are regarded as a reorganization of the ongoing EEG. According to this view, ERP can be generated by a selective and time-locked enhancement of a particular frequency band or at least in part by a phase resetting of ongoing frequencies (Quiroga 2006, Basar 1999a, 1999b). In particular, the study of event-related oscillations (EROs) in the frequency domain have been explored by some researchers on the effort to establish the interrelationship between EROs and ERP (Mecklinger *et al* 2007, Pfurtscheller and Lopes da Silva 1999a, 1999b, Klimesch 1999).

The neural fundamental of the ERP is crucial for us to gain deeper understanding on neurofunctional mechanisms induced by different cognitive processing. Unfortunately, still there is no concrete conclusion on the genesis of the ERP despite the huge amount of research and studies that have been carried out. The main difficulty is that the results shown so far vary from one work to another and even contradict each other. Specifically, a few are supporting solely additive response theory (for example, in Shah *et al* (2004), Mäkinen *et al* (2005), Mazaheri and Jensen (2006)), some are backing the phase reset model (for instance, in Sayers *et al* (1974), Makeig *et al* (2002), Gruber *et al* (2005), Hanslmayr *et al* (2007)), while others are in favor with the combination of the two theories (for example, findings in Min *et al* (2007), Fuentemilla and Grau (2006), Fell *et al* (2004)). The most reliable evidence for the phase-reset model perhaps is the phase concentration during the absence of power increase (Makeig *et al* 2004). Nevertheless, it can still be argued that phase concentration is due to an evoked response masked by a decrease in power or with an amplitude too small to cause a significant increase in power (Klimesch *et al* 2006). In addition, more efforts to dissociate the two hypothesized theories are also reported in Yeung *et al* (2004), (2007), but found to be unsuccessful. Precisely, the problem was the proposed analysis that is valid for determining the ERP peaks result from synchronized oscillations produced the same results when tested on a set of simulated EEG data which is based on additive theory.

Recently, a comprehensive review on ERP genesis was given in Sauseng *et al* (2007) where the evidence for the two models was presented and validated. Again the authors stressed that the question of ERP generation has not yet been convincingly answered although some evidence showed that the mixture of both mechanisms is most probable. A meaningful remark from the authors is the suggestion that oscillations play an important role in the timing of cortical information processing. Based on this assumption, the phase of an ongoing oscillation must undergo an event-related reorganization during or after the processing of a stimulus or task. If the phase would not be reset to a certain value (reflecting an optimal level of excitability), not more than half of the incoming stimuli could be processed under optimal conditions because the other half would fall into the comparatively more inhibitory cycle of oscillatory activity (Klimesch *et al* 2007a, 2007b).

From the accumulated information and evidence we could not disregard the hypothesis supporting the phase reset process in generating the ERP. Motivated by this, we propose a new signal processing tool in order to study the EEG phase reset particularly due to auditory attention through a time-scale approach which is based on the phase information of single sweeps. For the first time, an inverse analysis of the instantaneous phase is used for the purpose mentioned above. Our assumption is that if the phase of ongoing oscillations undergoes resetting (at a certain frequency band and an interval) to a particular phase value, it generates the ERP peaks. Specifically, we reset the phase of the EEGs at the frequency band associated with selective auditory attention to the mean phase of the ongoing EEGs at the specific interval where the ERP component is located. We expect an enlargement of the component due to the phase alignment of the attention related frequencies. Results obtained show direct connections between EEGs and ERP and provide strong evidence that the phase reset of EEGs plays an important role in the ERP generation. This finding strengthens the previous studies of phase reset theory in the generation of the ERP.

2. Materials and methods

2.1. Experimental procedures and data preparation

Ten student volunteers (aged 26.7 ± 2.5, four females) from Saarland University entered the study. All subjects provided informed consent prior to participation. The experiments were conducted in accordance with the Declaration of Helsinki. Auditory late responses (ALRs) were obtained by using a commercially available bioamplifier (g.tec USBamp, Guger Technologies, Austria). In the experiment which lasted for 20 min, three different frequency tones of 40 ms were each delivered in random order to the right ear at randomized inter-stimulus intervals (ISIs) of 1–2s. Meanwhile, the left ear was presented with relaxing music as a distracter. The randomized stimulation paradigm was used to maximize the entropy of the experiment such that maximum attention is required to solve the task (Low *et al* 2007). During the first 10 min of the experiment, subjects were required to pay attention to the stimulus and detect the target tones. After that subjects were instructed to stay in a relaxed condition for another 10 min. Single sweeps, i.e., the responses to the individual tones, were recorded using electrodes placed at the left and right mastoids, the vertex and the upper forehead. Electrode impedances were strictly maintained below 5 kΩ in all measurements (filter cut-off frequencies: 2–30 Hz, sampling frequency: 512 Hz). An artifact filter was used to remove responses that exceeded 50 μV. In preparing the data for further analysis, the recorded responses were divided into two groups named as attention and no attention data sets. Each of the data sets contains a total of 1000 single sweeps (i.e., 100 sweeps from every subject).

2.2. Continuous wavelet transform and its inverse

Let $\psi_{s,\tau}(\cdot) = |s|^{-1/2}\psi((\cdot - \tau)/s)$, where $\psi \in L^2(\mathbb{R})$ is the wavelet satisfying the admissibility criterion: $0 < \mathcal{C}_\psi = \int_{\mathbb{R}} \frac{|\Psi(\omega)|^2}{|\omega|}\,\mathrm{d}\omega < \infty$, where $\mathcal{C}_\psi$ denotes the admissibility constant, $\Psi(\omega)$ is the Fourier transform of the wavelet ψ and $s, \tau \in \mathbb{R}, s \neq 0$. The wavelet transform $\mathcal{W}_\psi : L^2(\mathbb{R}) \longrightarrow L^2\big(\mathbb{R}^2, \frac{\mathrm{d}s\,\mathrm{d}\tau}{s^2}\big)$ of a signal $f \in L^2(\mathbb{R})$ with respect to the wavelet ψ is given by the inner L^2-product:

$$(\mathcal{W}_\psi f)(s,\tau) = \langle f, \psi_{s,\tau}\rangle_{L^2}. \tag{1}$$

In the current study, the implementation of the wavelet transform is done in Fourier space by means of fast Fourier transform (FFT). We used the complex Morlet function as the wavelet and ω_0 (nondimensional frequency) was taken as 6 to satisfy the admissibility condition. Note that for this value of ω_0, the Morlet wavelet and the wavelet scale are almost identical to the Fourier period (Torrence and Compo 1998).

The wavelet transform in (1) is a complete, stable and highly redundant representation of signals. Consequently, the original signal can be obtained from its wavelet transform by integrating over all scales and locations. However, it is also possible to reconstruct the original signal by using a completely different wavelet function. We can even choose a delta distribution due to the redundancy of continuous wavelet transform (Farge 1992). This gives a rather simple and fast reconstruction formula:

$$f = \frac{1}{\mathcal{C}_\delta} \int_{\mathbb{R}} (\mathcal{W}_\psi f)(s, \tau) \frac{\mathrm{d}s}{s^{1/2}}, \tag{2}$$

where $\mathcal{C}_\delta$ is the reconstruction of a δ distribution from its wavelet transform using the wavelet $\psi_{s,\tau}$. Note that $\mathcal{C}_\delta$ is scale independent and is a constant for each wavelet function.

2.3. Phase stabilization

The wavelet transform described by (1) with a complex wavelet generates a complex representation which can be divided into its real part $\mathrm{Re}((\mathcal{W}_\psi f)(s, \tau))$ and its imaginary part $\mathrm{Im}((\mathcal{W}_\psi f)(s, \tau))$. Alternatively, in polar form

$$(\mathcal{W}_\psi f)(s, \tau) = |(\mathcal{W}_\psi f)(s, \tau)| \, \mathrm{e}^{\imath \arg((\mathcal{W}_\psi f)(s,\tau))},$$

where $|(\mathcal{W}_\psi f)(s, \tau)|$ describes the instantaneous amplitude and $\arg(\mathcal{W}_\psi f)(s, \tau)$ denotes the instantaneous phase.

First, the mean phase of a sequence $\mathcal{F} = \{f_m \in L^2(\mathbb{R}) : m = 1, \ldots, M\}$ of M sweeps was extracted from the average of single sweeps. Let $\mathcal{F}_{erp}$ is the average of the sequence $\mathcal{F}$, the mean phase $\Theta_{s,\tau}$ is determined by

$$\Theta_{s,\tau}(\mathcal{F}) = \arg[(\mathcal{W}_\psi \mathcal{F}_{\mathrm{erp}})(s, \tau)]. \tag{3}$$

For every individual single sweep f_m, we do the following:

(i) The phase $\theta_{s,\tau}(f_m)$ was determined and shifted to the mean phase:

$$(\mathcal{W}'_\psi f_m)(s, \tau) = (\mathcal{W}_\psi f_m)(s, \tau) \, \mathrm{e}^{\imath(\Theta_{s,\tau}(\mathcal{F}) - \theta_{s,\tau}(f_m))}, \tag{4}$$

where $(\mathcal{W}'_\psi f_m)(s, \tau)$ is the phase-shifted wavelet coefficients.

(ii) In order to reconstruct the phase-stabilized signal, an inverse transform was performed. In this way, the real part of the wavelet transform over all scales (denoted as i) is summed up (Farge 1992, Torrence and Compo 1998):

$$f_m = \frac{\mathrm{d}j \, \mathrm{d}t^{1/2}}{\mathcal{C}_\delta \psi_0(0)} \sum_{i=0}^{i_{\mathrm{total}}} \frac{\mathrm{Re}\{(\mathcal{W}'_\psi f_m)(s, \tau)\}}{s_i^{1/2}}. \tag{5}$$

dt and dj are the sampling period and scaling interval, respectively. The factor $\psi_0(0)$ removes the energy scaling, while $s_i^{1/2}$ converts the wavelet transform to an energy density, $\mathcal{C}_\delta$ is the reconstruction factor as mentioned in section 2.2.

2.4. Phase stability measure

According to Strauss *et al* (2008a), the phase stability $\Gamma_{s,\tau}$ is defined by

$$\Gamma_{s,\tau}(\mathcal{F}) = \frac{1}{M} \left| \sum_{m=1}^{M} \mathrm{e}^{\imath \arg((\mathcal{W}_\psi f_m)(s,\tau))} \right|. \tag{6}$$

Equation (6) yields a value in the range of 0 and 1. We have a perfect phase stability for a particular s and τ for $\Gamma_{s,\tau} = 1$ and a decreasing stability for smaller values.

2.5. Evoked power and total power calculations

The evoked power is computed as

$$P_{\text{evoked}}(s,\tau)(\mathcal{F}) = |(\mathcal{W}_{\psi}\mathcal{F}_{erp})(s,\tau)|^2. \tag{7}$$

In order to estimate the evoked and induced activity, the total power is calculated in the following way: we compute the wavelet transform of the EEG, then we take the squared modulus of the samples and, finally, the average of these qualities over the sweeps.

$$P_{\text{total}}(s,\tau)(\mathcal{F}) = \frac{1}{M}\sum_{m=1}^{M}|(\mathcal{W}_{\psi} f_m)(s,\tau)|^2. \tag{8}$$

2.6. Phase noise effect

We are also interested to inspect how the phase noise (i.e., phase deviation) affects the generation of the ERP. Assuming the phase across single sweeps is normally distributed, phase jitters can be applied by introducing a fluctuating constant Δ. Here Δ is bounded in the range of 0 to π. In order to avoid the jump between 0 and 360°, we are concerned with the positive fluctuation range. A new mean phase $\Theta'_{s,\tau}(\mathcal{F})$ was randomly chosen from the defined interval as

$$\Theta'_{s,\tau}(\mathcal{F}) = [\Theta_{s,\tau}(\mathcal{F}), \Theta_{s,\tau}(\mathcal{F}) + \Delta]. \tag{9}$$

The phase-shifted wavelet transform in (4) gives

$$(\mathcal{W}''_{\psi} f_m)(s,\tau) = (\mathcal{W}_{\psi} f_m)(s,\tau)\,\mathrm{e}^{\iota(\Theta'_{s,\tau}(\mathcal{F}) - \theta_{s,\tau}(f_m))}. \tag{10}$$

3. Results

The positive averaged difference of the power

$$P_{\text{diff}}(s,\tau) = \left|\left(\mathcal{W}_{\psi}\mathcal{F}^{a}_{\text{erp}}\right)(s,\tau)\right|^2 - \left|\left(\mathcal{W}_{\psi}\mathcal{F}^{u}_{\text{erp}}\right)(s,\tau)\right|^2 \tag{11}$$

between the averaged attended (denoted by $\{\mathcal{F}^{a}_{erp}\}$) and averaged unattended (denoted by $\{\mathcal{F}^{u}_{erp}\}$) data sets is shown in figure 1. This figure is called a wavelet spectrogram or scalogram, which is produced by the square modulus of the wavelet transform. Note that both data sets have an equal number of single sweeps. As shown in the figure, the main difference between attention and no attention was found at the scales from 48 to 55 although it did not reach significance. These scales are corresponding to a frequency range of 6–10 Hz. Thus, we termed this frequency band the theta–alpha border. We suggest that this frequency range is closely related to auditory attention.

Figure 2(a) depicts the averaged set of sweep $\mathcal{F}$ for original attention data as well as their phase-modified reconstruction. We show that the phases of the EEGs (scales from 48 to 55) were stabilized at the duration where the N100 wave is presented (i.e., approx. 70–130ms). The neural activity reflected in this wave is presumably associated with the auditory cortex (Hall 1992, Verkindt *et al* 1995) and it is commonly used in paradigms related to auditory attention (Hillyard *et al* 1973, Naatanen and Michie 1979, Janata 2001, Woldorff *et al* 1987). This wave is assumed to reflect selective attention to basic stimulus characteristics, initial selection for later pattern recognition and intentional discrimination processing. Its amplitude is enhanced by increased attention to the stimuli (Hillyard *et al* 1973, Ritter *et al* 1988). As illustrated in the figure, an enlargement of the N100 wave for attention data after the phase stabilization is apparent, and thus significantly different from the original signal (ANOVA, $p < 0.05$).

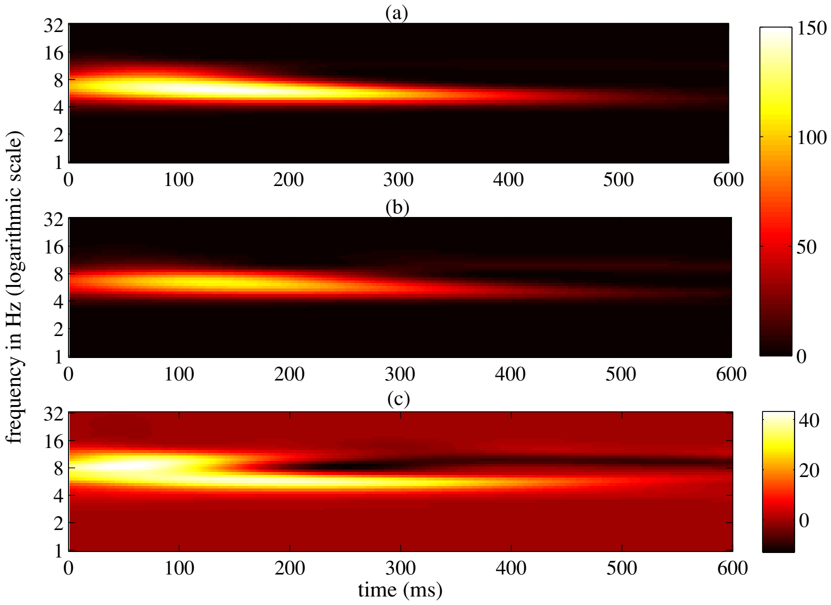

Figure 1. Wavelet spectrogram of averaged EEGs for (a) attended, (b) unattended and (c) the difference between attended and unattended. Note that the color map returns a smooth color change from black for smaller values to white for larger values. The main difference between attended and unattended activities was found at a frequency range of 6–10 Hz, which is associated with attention.

Figure 2(b) illustrates the normalized averaged difference of phase stability for attention data before and after the phase stabilization, respectively. Note that the wavelet transform for scale $s = 54$ is shown in the figure. This scale can be associated with a frequency of about 6.4 Hz. Once more, the most significant difference ($p < 0.05$) of the phase stability is found within the time interval between 70 and 130 ms, where the N100 wave is located. As expected, the phase stability of the reconstructed data is much larger due to higher phase coherence after the phase stabilization.

We also evaluated the evoked power and the total power from the time-scale coefficients before and after phase modification. Evoked and total power were calculated according to section 2.5 and the results are shown in figure 3. The increase of evoked activities is noticeable for phase-stabilized signals in the theta–alpha frequencies due to phase stabilization. In contrast, there is only little difference in the total power at around 5–10 Hz after the phase modification.

Based on the description in section 2.6, the effects of phase noise in ERP generation have been investigated. We introduced three noise intervals named $\mathrm{Int}_1(\Delta)$, $\mathrm{Int}_2(2\Delta)$ and $\mathrm{Int}_3(3\Delta)$. Δ was set as 1. The analysis was carried out a total of 30 times at each interval and then the amplitudes of the N100 wave were averaged. The results are summarized in table 1. As the phase noise interval became larger, the value of the amplitude decreases gradually.

The relationship between attention data and no attention data was studied by resetting the phase of no attention data at the theta border to the mean phase of attention data at the same frequency range. We found that the amplitude of the N100 wave is enlarged and the result

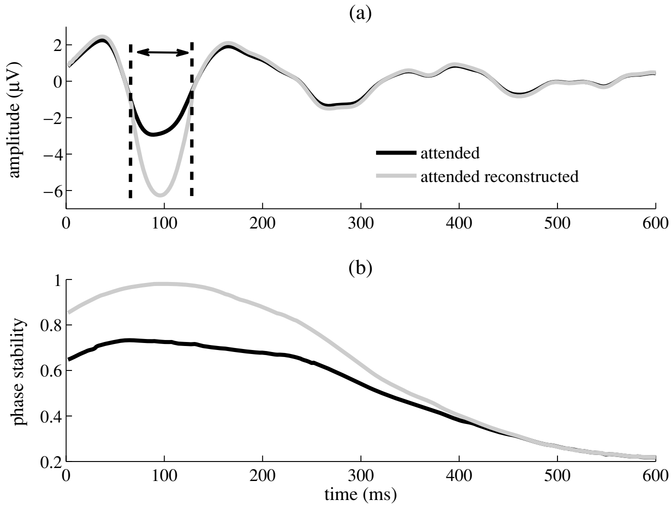

Figure 2. (a) Amplitude of averaged attended EEGs before and after phase reset at the theta–alpha border (i.e., $s = 48$–55). Note that the phases of the EEGs have been reset at around 100 ms, where the N100 wave is located. This interval is shown in the figure by two vertical dotted lines and a double arrow within. (b) The normalized averaged difference of phase stability for $s = 54$ as example before and after phase reset at the theta–alpha border. Significant differences are found for the amplitude and the phase stability before and after the phase reset at the N100 wave (ANOVA, $p < 0.05$).

Table 1. Summary of the averaged amplitude (N100 wave) of reconstructed phase-modified EEGs for different intervals of phase noise.

	Phase noise intervals		
	$\mathrm{Int}_1\,(\Delta)$	$\mathrm{Int}_2\,(2\Delta)$	$\mathrm{Int}_3\,(3\Delta)$
Amplitude (μV)	−6.6041	−6.4092	−5.7276

Note: Δ was set as 1.

looks similar to the attention data. This is shown in figure 4. We hypothesize that modifying the phase in this frequency range could alter the level of attentiveness and it is reflected by a change of the N100 wave.

4. Discussion

We have presented a new approach to the investigation of the phase reset in the EEG due to auditory attention using an inverse analysis of the instantaneous phase. This method sheds light on the importance of the EEG phase reorganization in the generation of the ERP and thus illuminates the relationship between ongoing oscillations and the ERP.

According to the brain oscillation theory, it is well known that different frequencies reflect distinct neural processing systems in the ongoing EEG. In relation to this, our experimental data show that the theta–alpha border is associated with auditory attention (figure 1). Apart from that, there is also literature suggesting that the lower alpha activity (8–10 Hz) is clearly linked to attention (Herrman and Knight 2001, Yordanova *et al* 2001).

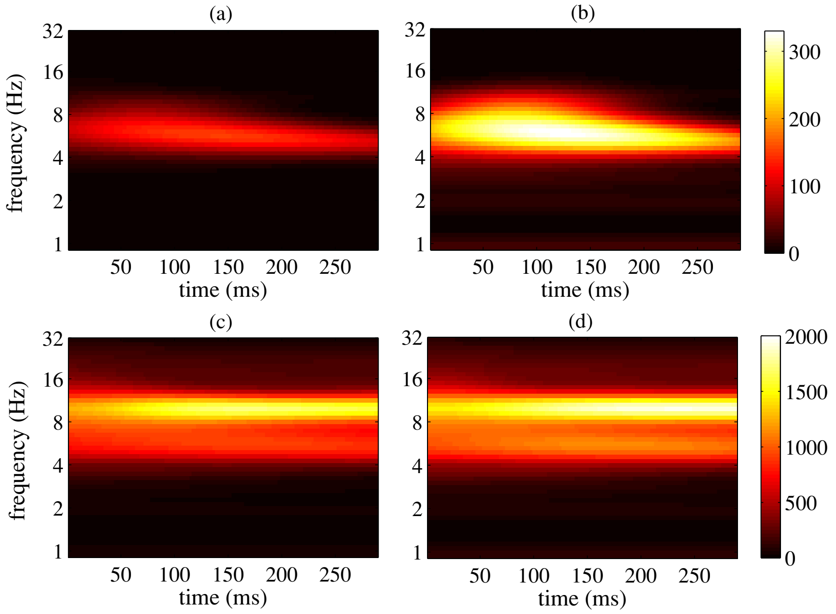

Figure 3. Wavelet spectrogram of EEGs for attended data set before and after phase reset at the theta–alpha border. Evoked power (a) before and (b) after phase stabilization. Total power (c) before and (d) after phase stabilization. Note that there is a remarkable increase of evoked activities at the N100 wave but almost no change of the total power after the phase stabilization. Results support the idea that a reset of phase will not lead to a power change.

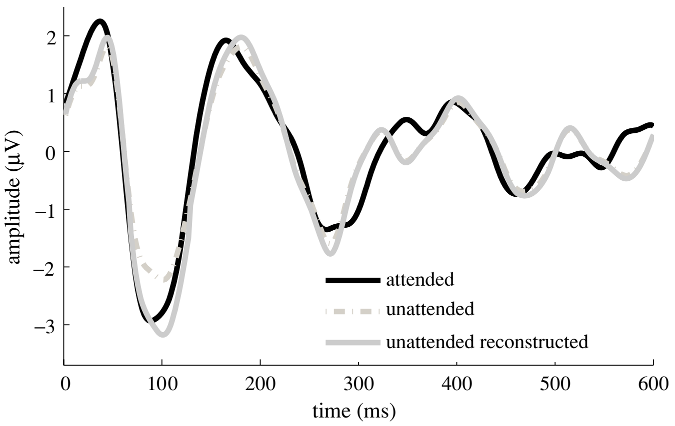

Figure 4. Amplitude of averaged EEGs after the phase reset of unattended data to the mean phase of attended data at the theta border (at the N100 wave duration). It is shown that the amplitude of the N100 wave is enlarged and it resembles the attention data.

Besides that, evidence strongly suggested that ongoing alpha phase controls cortical activation. This means that an alpha wave is capable of controlling the timing of cortical activation in the range of milliseconds (Klimesch *et al* 2007a). It has been argued that alpha activity might play a similar role in event-related processes, that the phase of alpha must be reset at some point of time during or after the presentation of the stimulus in order to

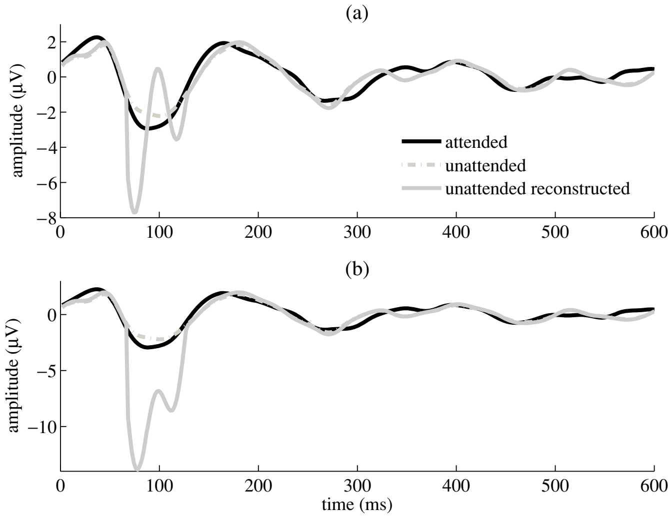

Figure 5. (a) Amplitude of averaged EEGs after the phase reset of unattended data to the mean phase of attended data at the beta band (13–30 Hz). (b) Amplitude of averaged EEGs after the phase reset of unattended data to the mean phase of attended data at the whole frequency band (2–30 Hz).

enable a torrent of diverse processes that require precise timing and coordination. For the case of auditory stimulation, we assumed that the phase reset is taken place around the N100 wave, such that the phase reset may be considered as an early inhibitory filter that enables the emergence of a highly selective and excitatory encoding network (Klimesch *et al* 2007a).

Due to phase stabilization at the theta–alpha border, the so-called randomly distributed phase in this frequency range has been reset to start from the mean phase for a short period of time. This leads to a burst of evoked activity, since oscillations sum up if they have identical phases across sweeps (this phase coherence is shown by the higher phase stability after the phase reset). The result obtained is in accordance to the idea of Sauseng *et al* (2007) that considerable phase resetting might generate evoked activity. On the other hand, there is only very little change of total power at the respective theta–alpha border. This result shows in agreement with what has been reported in the literatures that if the ERP is generated at least in part by a phase resetting of ongoing frequencies, there is little change or no change of the power. If we observe carefully, there is a very small increase of power at the theta range. This occurrence can be associated with the widely documented theta event-related synchronization (ERS) in a large variety of different tasks. It has been reported that theta synchronizes, whereas alpha desynchronizes during actual cognitive performance (Doppelmayr *et al* 1998, Klimesch 1999, Klimesch *et al* 2004, 2007a). Additionally, a recent study of auditory Go/NoGo ERPs (Barry 2008) showed evidence for phase reset (phase realignment) prior to 100 ms, as N100 wave develops in both Go/NoGo responses. Note that this phase reset again involves delta, theta and alpha bands.

By accepting the phase reset as one of the possible mechanisms in generating the ERP, one might anticipate the phase jittering across sweeps will certainly give influence to the extent of the ERP generation. In order to confirm this assumption, we created a few phase noise ranges and the effect of each level of noise toward the ERP generation has been determined by evaluating the amplitude of the N100 wave. As expected, our results show that the smaller the phase variation across sweeps, the more negative the N100 wave. This implies that a preferred phase is required for EEG sweeps in order to produce components of the ERP (here we refer to the N100 wave).

Resetting the phase only at the theta border of no attention data to the mean phase of attention data leads to an enlargement of the amplitude of no attention data. Interestingly, the averaged amplitude of no attention data resembles the attention data. This might be an indicator to the fact that theta activity reflects unspecific factors such as attentional demands, task difficulty and cognitive load (Klimesch 1999). We hypothesize that modifying the phase in the frequency range where the main difference exists could change the level of attentiveness and the neural correlates of attention can be reflected by the proposed phase stability measure.

It is also interesting to examine phase reset of no attention data at different frequency bands besides the theta border. For this purpose, we stabilized the phase at the whole frequency range (2–30 Hz) as well as the phase at the beta range (13–30 Hz) for comparison. The procedures are the same as before and the results are illustrated in figure 5. The appearance in terms of the shape of the reconstructed ERPs for both frequency ranges are not well correlated with the N100 wave. These findings indicate that the ongoing oscillations are functionally relevant for a task and thus phase reset seems unavoidable (Klimesch *et al* 2007).

5. Conclusion

We have presented a novel approach which demonstrates the impact of the phase reset in EEG data. It is the first time that an inverse analysis of the instantaneous phase is introduced in investigating the phase reset of the EEGs due to auditory attention. The outcomes reveal that there exists an indispensable interrelationship between EEGs and ERP that related to the generation of the ERP. Particularly, the presentation of an auditory stimulus triggers the phase reset process at the theta–alpha border which leads to the emergence of the N100 wave. This suggestion provides a reinforcement of other studies. It is concluded that the phase reset of EEGs plays a very important role in the ERP generation. We would like to emphasize that this work was not intended to solve the issue of the ERP generation or to distinguish the competing theories, however the aim was to gain deeper insights on the impact of the EEG phase reset by using an inverse transform method for the first time.

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