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Detection of early cognitive processing by event-related phase synchronization analysis

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In order to investigate the temporal characteristics of cognitive processing, we apply multivariate phase synchronization analysis to event-related potentials. The experimental design combines a semantic incongruity in a sentence context with a physical mismatch (color change). In the ERP average, these result in an N400 component and a P300-like positivity, respectively. The synchronization analysis shows an effect of global desynchronization in the theta band around 288 ms after stimulus presentation for the semantic incongruity, while the physical mismatch elicits an increase of global synchronization in the alpha band around 204 ms. Both of these effects clearly precede those in the ERP average. Moreover, the delay between synchronization effect and ERP component correlates with the complexity of the cognitive processes.

Key words: phase synchronization; coherence; semantic incongruity; color change; N400; P300; theta; alpha

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INTRODUCTION

Effects of experimental manipulations observed in the averaged event-related potential (ERP) are characterized by their latency (among other parameters). Traditionally, cognitive processing has been associated with ERP effects occurring several hundred milliseconds after the presentation of the critical stimulus, the so-called endogenous components [1]. By contrast, it has been shown that ERP components as early as the P50 and N100 can be modulated by attention [2, 3] and are therefore apparently related to cognition. For the area of higher cognitive functions, Dogil et al. [4] recently hypothesized that all the processes that are elicited by a stimulus start immediately with its presentation, but only after a delay become visible in the ERP average. If this is the case, it should be possible to observe earlier stages of cognitive processing than those appearing in the form of ERP components by means of alternative techniques of time series analysis.

In the last years there has been an increasing number of studies on the spectral composition of event-related potentials. For instance, Yordanova et al. [5, 6] reported a relationship between the auditory oddball P300 component and alpha band power, while other authors [7, 8] additionally stated a correlation with effects in the delta and theta band. For the area of language processing, Röhm et al. [9] postulated a relation between semantic memory demands and the alpha band, and Bastiaansen et al. [10] found theta band power effects for a syntactic violation. Röhm et al. [11] were able to dissociate two types of N400 based on their relation to the theta and delta bands, respectively.

Going a step beyond spectral analysis, a promising line of research is based on the hypothesis that functional integration of brain areas is achieved by the synchronous oscillation of neuron populations [12]. The discovery of the phenomenon of phase synchronization in nonlinear dynamics [13] directed attention to the fact that synchronization strength should not be quantified by coherence, but by a nonlinear measure that takes only the phase of oscillations into account. Subsequently, phase synchronization analysis has successfully been applied to EEG data [14].

In this paper, we make use of the methods of multivariate phase synchronization analysis introduced by Allefeld et al. [15, 16] to obtain information on early cognition-related processing. They are applied to experimental data obtained within a "classic" psycholinguistic paradigm following Kutas and Hillyard [17]. Short German sentences were visually presented. In the trials of the *control* condition, the sentence was normal and meaningful and it was shown in a uniform color (green or red). In the *semantic incongruity* condition the terminal verb of the sentence had the same color as the beginning but did not make sense in the given context. And in the *physical mismatch* condition the verb made sense but it was presented in the other color. This design, combining a semantic incongruity with a physical mismatch condition, allows us to observe electrophysiological effects of two cognitive processes of different complexity.

MATERIALS AND METHODS

16 subjects (8 females) participated after informed consent. They were right-handers, monolingual speakers of German, 20–27 years old, and had normal or corrected-to-normal vision.

Sentences were presented in a word-by-word manner on

Condition		Example			
(1)	control	Die	Maus	wurde	gejagt.
		The	mouse	was	chased.
(2)	semantic incongruity	Die	Maus	wurde	bepflanzt.
		The	mouse	was	planted.
(3)	physical mismatch	Die	Maus	wurde	gejagt.
		The	mouse	was	chased.

Table 1: Sample stimuli for each of the three experimental conditions. Dark and light shades of gray represent the colors red and green, respectively.

a 17″ computer screen. The three experimental conditions are illustrated in Table 1. The language material consisted of 52 pairs of sentences adopted in modified form from [18]. They were chosen such that by exchanging the terminal verbs in each pair, a semantic incongruity is generated. Each of the four resulting sentences was shown in matching and mismatching colors. Those trials with combined semantic and physical violation were kept as a filler condition to achieve a balanced design. The colors green and red occurred with the same frequency, for the beginning as well as the verb, to avoid any predictabilities. Trials were presented in a randomized order in eight blocks, with a minimum distance of one block between the two occurrences of each sentence. The order was reversed in pairs of subjects to avoid sequence effects. Experimental blocks were preceded by two short training blocks.

Words were presented for 400 ms each, with 100 ms in between. 800 ms after the verb a probe word was presented. The task of the subject was to indicate by a button press within 3.5 s if the probe had occurred in the preceding sentence in the same way (including color), to check whether the sentence had been perceived correctly. Probes were either the verb or the noun of the preceding sentence or semantically related alternatives. They were balanced for correctness and word category (verb/noun). After a pause of 1 s, the next trial started.

EEG was recorded with a sampling rate of 250 Hz from 59 Ag/AgCl scalp electrodes (impedances $\leq 5\,\mathrm{k}\Omega$). EOG was monitored. For trials in which the subject had given the correct answer, artifact-free epochs from -600 to 1300 ms relative to the presentation of the critical word (the verb) were selected for processing.

For the mean ERP, the EEG data were re-referenced to the mean of mastoids, epochs were averaged for each subject and condition, and the result was baseline-corrected (300 ms prestimulus). For the synchronization analysis, the spherical spline Laplacian algorithm [19] was applied to reduce spurious EEG signal correlations due to volume conduction. A complex Morlet wavelet (center frequency to bandwidth ratio $= 7$) was used to obtain time-frequency phases $\phi(t, f)$ and amplitudes $a(t, f)$. For each subject, condition, frequency band and time instant separately, the phases ϕ_{ik} and amplitudes a_{ik} at electrode i of epoch $k = 1 \ldots n$ entered the analyses. The basic measures are the pairwise *synchronization strength*

$$\bar{R}_{ij} = \left| \frac{1}{n} \sum_k \exp\left(\mathrm{i}(\phi_{jk} - \phi_{ik})\right) \right| ,$$

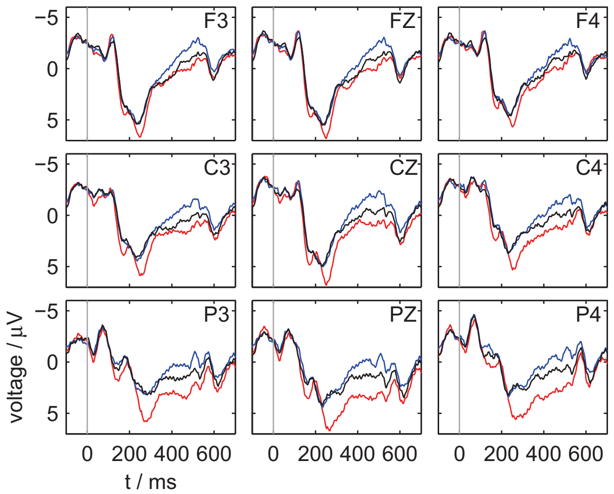

Figure 1: Average ERP at nine electrodes for the control (black), semantic incongruity (blue), and physical mismatch condition (red line).

and the pairwise *magnitude coherence*

$$MC_{ij} = \left| \frac{1}{\sqrt{\sum_k a_{ik}^2 \sum_k a_{jk}^2}} \sum_k a_{ik}\, a_{jk}\, \exp\left(\mathrm{i}(\phi_{jk} - \phi_{ik})\right) \right| ,$$

the modulus of the complex correlation coefficient (i denotes the imaginary unit). While MC is a measure of the linear dependency of signals, $\bar{R}$ is the corresponding nonlinear quantity (derived by neglecting amplitude variations) that is specifically tailored to detect synchronization of self-sustained oscillators [16]. To obtain global measures of synchronization and coherence, the $\bar{R}_{ij}$ and MC_{ij} were averaged over all electrode pairs. An index $\bar{R}_{i\mathrm{C}}$ of the local participation of each electrode i in the global synchronization process was calculated from the matrix of bivariate synchronization strengths $\bar{R}_{ij}$ by means of the synchronization cluster analysis introduced in [15]. It was applied to a subset of 27 electrodes to further reduce spurious correlations.

Results presented in the following are the average over subjects per condition, the pairwise t-statistic difference between conditions over subjects, or a z-statistic difference between conditions over subjects based on a pairwise permutation test [20], respectively. To obtain an unbiased latency measure that can be used to compare the timing of ERP average and synchronization effects, the peak latency according to the t-statistic difference between conditions was determined. We chose this approach in favor of a measure of onset latency because it does not depend on an arbitrarily chosen threshold, and because it is robust against the time "smearing" implicit in the wavelet transform (its finite temporal resolution).

RESULTS

Figure 1 shows the results for the average ERP. The semantic incongruity elicits a negativity relative to the control condition around 500 ms after stimulus presentation, the expected N400 ERP component ($p = 0.0012$ between 450

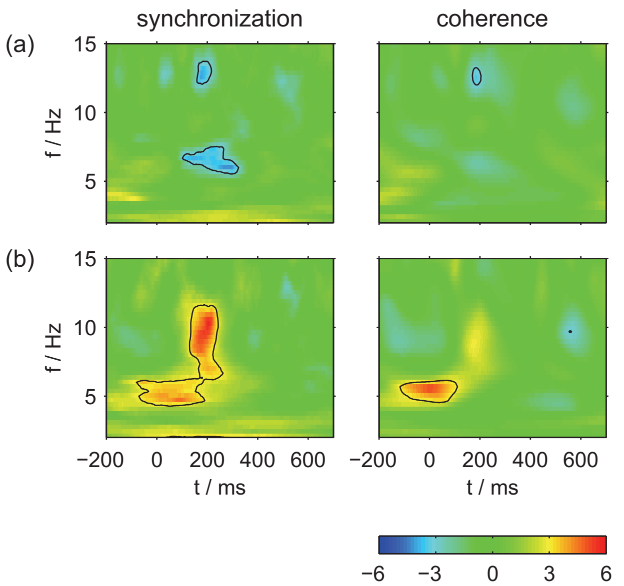

Figure 2: Time-frequency plots of the t-statistic difference of the global synchronization (left column) and coherence measures (right column) between the semantic incongruity (a) and physical mismatch (b) conditions and the control condition, respectively. Contours indicate those areas where the threshold for a two-sided test at a level of 1 % is exceeded. To account for multiplicity of testing, the corresponding false discovery rate [21] was determined to be 0.296, which means that at least 70 % of the area within the contours can be taken to indicate a real difference between conditions. Frequencies above 15 Hz were included in the analysis, but there were no reliable effects.

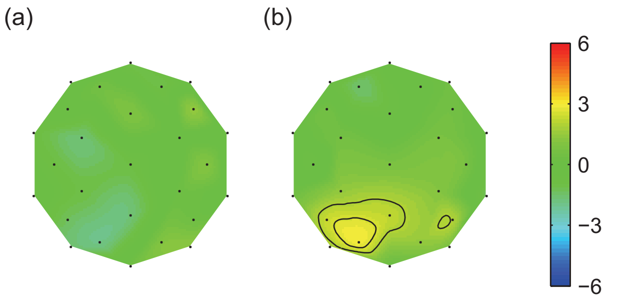

Figure 3: Differences in the synchronization topography between (a) the semantic incongruity and control conditions at 288 ms and 6 Hz and (b) the physical mismatch and control conditions at 204 ms and 10.333 Hz. The displayed quantity is a z-statistic derived from a permutation test, interpolated between the values at the electrode locations (dots). Contours indicate the thresholds for two-sided tests at levels 1 % and 5 %.

and 550 ms; average over electrodes of Fig. 1). The physical mismatch elicits a positivity around 300 ms similar to a standard P300 component ($p < 0.001$ between 250 and 350 ms). The peak latencies of these effects at the different electrodes range from 492 ms to 528 ms (median 504 ms) for the N400 and from 252 ms to 336 ms (median 268 ms) for the positivity.

In Fig. 2, time-frequency plots of the t-statistic difference between conditions for the global synchronization and coherence measures are shown. In interpreting these plots, the specific sensitivity of the two different measures has to be considered. A linear dependency between activity measured at different scalp sites can be caused by the simple propagation of a signal generated in one area of the brain into another. This dependency will affect the phases as well as the amplitudes of the recorded signals and therefore can be detected by both measures. In contrast, phase synchronization of self-sustained oscillators leaves the amplitude dynamics free [13], leading to a reduced response of the coherence measure. Following this, we consider only those effects in the global synchronization as reflecting genuine changes of neuronal phase synchronization that do *not* show up in the global coherence as well.

According to this criterion, there is only one synchronization effect for each of the two experimental manipulations. The semantic incongruity (Fig. 2a) elicits a decrease in global synchronization peaking around 288 ms after stimulus presentation and frequency 6 Hz. The physical mismatch (b) elicits an increase in global synchronization peaking around 204 ms and 10.333 Hz.

To determine the scalp distribution of synchronization effects, the synchronization cluster analysis [15] was applied to obtain indices $\bar{R}_{iC}$ of local participation in the global synchronization cluster for the two peak time-frequency points resulting from the global measure. The difference of synchronization topographies between the respective experimental condition and the control condition is shown in Fig. 3. For the semantic incongruity (a) it was not possible to localize the global desynchronization effect, because the broadly distributed contributions do not reach significance at any single electrode. For the physical mismatch (b), the global increase of synchronization is concentrated mainly in the left and to a small part in the right parieto-occipital area.

DISCUSSION

The results obtained by the ERP averaging analysis replicate previous findings [17]. An N400 effect is found for the semantic incongruity, and it is clearly different from the effect of a comparable manipulation regarding the physical properties of the stimulus, which elicits a P300-like component. The phase synchronization analysis on its part firstly confirms these results: semantic and physical violation elicit distinct and clearly different effects going into opposite directions, decreased and increased synchronization. These observations may be interpreted in such a way, that the attempt to build a semantic structure reflecting the meaning of the sentence fails in the case of the incongruent verb, which leads to a decrease of functional integration of brain areas involved in language processing. On the other hand, the change of the color constitutes an unmet expectation, delivering new information that has to be actively integrated.

Beyond this, the attempt to observe earlier stages of cognitive processing by means of alternative measures of brain activity has been successful. Even the earliest peak latencies in the ERP average are clearly preceded by those of the synchronization effects: 288 ms poststimulus vs. 492 ms for the semantic incongruity, 204 ms vs. 252 ms for the physical mismatch. Apparently, the processing of both violations begins earlier than should have been expected from the timing of the corresponding ERP components. Moreover, the time delay between synchronization and ERP average effects (204 ms for the semantic, 48 ms for the physical violation) correlates with the complexity of the respective cognitive process. It appears that (consistent with the hypothesis of [4]) both processes start at approximately the same time after the presentation of the critical stimulus, but while the processing of the simple color change is quickly done, the full resolution of the semantic incongruity takes a much longer time.

The difficulty to localize the effect of the semantic incongruity indicates an involvement of broadly distributed brain areas, which is consistent with the topography of the N400 component [22, 23]. With regard to previous studies [5, 6, 11], the current experiment supports the assumptions that a P300 component induced via a physical mismatch can be correlated with an increased activity in the alpha band, whereas language-related semantic processing can be associated with changes of activity in the theta band. More importantly, if the observed differences reflect more general neurophysiological characteristics of higher cognition, one would expect that other P300 sources [5, 6] as well as different language tasks [10, 11] should show a similar pattern with respect to time-frequency behavior. In addition, it will be interesting to see in further research whether the observed correlation between phase synchronization and event-related brain potentials is a function of the increased activity in specific frequency bands or can be addressed to a particular cognitive processing operation.

CONCLUSION

The results reported here indicate that phase synchronization analysis of event-related potentials delivers results that can be related to those of the averaging technique, but that also substantially extend our knowledge about the neuronal processes underlying cognition. Further work will be necessary in order to support the current results and to establish results for other areas of higher cognition.

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