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Phase Synchronization Analysis of Event-Related Potentials in Language Processing

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Abstract. Phase synchronization analysis, including our recently introduced multivariate approach, is applied to event-related EEG data from an experiment on language processing, following a classic psycholinguistic paradigm. For the two types of experimental manipulation distinct effects in overall synchronization are found; for one of them they can also be localized. The synchronization effects occur earlier than those found by the conventional analysis method, indicating that the new approach provides additional information on the underlying neuronal process.

INTRODUCTION

The investigation of phase synchronization processes has received much attention in the past years, in the theory of nonlinear dynamics [1, 2] as well as in empirical sciences including neuroscience [3, 4]. In the context of the hypothesis that functional integration of different parts of the brain is achieved by the synchronous oscillation of neuron populations, phase synchronization analysis has already been applied to electroencephalographic (EEG) data [5].

Event-related potentials (ERPs) are the standard form of EEG data in cognitive science. EEG is recorded from a subject while stimuli of different classes are repeatedly presented (trials), and sections of the continuous EEG record that are temporally related to the presentation (epochs) are selected and processed separately for each stimulus class (the experimental condition). The conventional method of ERP evaluation is to compute the average of the epochs and to look for statistically significant differences between the waveforms for each condition (ERP components).

Phase synchronization analysis of ERPs is intended to complement this standard evaluation method. Extending known approaches to measure bivariate synchronization, we have previously proposed a new method of *multivariate* phase synchronization analysis [6]. The topic of the present paper is the application of this method to an ERP experiment on language processing, following a classic psycholinguistic paradigm.

The first ERP effect that has been specifically associated with language comprehension is the *N400 component*, found by Kutas and Hillyard [7]. It consists of a negative deflection in the ERP average that occurs about 400 ms after the presentation of a word which is semantically inappropriate in the given context. By combining this semantic deviation with a physical manipulation of the critical stimulus (larger font size), resulting in a positive deflection, they were able to show that the N400 is not caused by an

Table 1. Sentences illustrating the three experimental conditions. The critical word (the verb) is displayed in a separate column. Dark and light shades of gray represent the colors red and green, respectively. The sentences given here are just a sample from a large set.

1	Der Priester wurde	geholt.	The priest was called.
2	Der Priester wurde	asphaltiert.	The priest was asphalted.
3	Der Priester wurde	geholt.	The priest was called.

unexpected stimulus in general. The N400 is one of the most important, reliably reproduced and well investigated language-related ERP components [8]. Because of this, to provide a basis for a first exploration of neuronal synchronization processes in language comprehension, the study of Kutas and Hillyard was replicated.

EXPERIMENTAL SETUP AND CONVENTIONAL ANALYSIS

In our experiment, German sentences (adopted from [9]) were visually presented word-by-word to the subject. Sentence presentations belonged to three experimental conditions (Table 1). In the first condition the sentence was normal and meaningful, and it was presented in a uniform color (green or red); this condition served as a *control*. In the second condition, the verb had the same color as the beginning of the sentence, but it did not make sense in the given context, it was *semantically incongruent*. In the third condition, the verb made sense but it was presented in the other color, it was *physically mismatching*. There was also a combined condition where the sentence contained an inappropriate verb and the verb was colored differently; this last condition is not further evaluated in this paper.

The language material used in the experiment consisted of 52 pairs of sentences. 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, such that there were 416 different trials in total, 104 of them for each condition. The trials were presented in a randomized order. In a trial, the words of the sentence were presented for 400 ms each, with 100 ms in between. After the verb a pause of 800 ms was interposed, followed by the presentation of a probe word. By this, the subject was prompted to indicate by a button press (within 3.5 s) if this word occurred in the preceding sentence in the same way, including color, to check if the sentence had been perceived correctly. The screen was blanked for 1 s before the next trial started.

The experiment was performed with 16 subjects (8 females). All were right-handers, university students, grown up monolingually (German), between 20 and 27 years old, and had normal or corrected to normal vision. EEG was recorded with a sampling rate of 250 Hz from 59 scalp electrodes (Fig. 1a). For those trials in which the subject had given the correct response to the probe word, artifact-free epochs from −600 to 1300 ms relative to the presentation of the critical item (the verb) were selected for processing.

To check if the replication actually reproduced the results of [7], the average of epochs for each condition was computed. Figure 1b shows the results for electrode PZ. As expected, the semantic incongruity elicited a negativity from 300 to 500 ms relative to the

Figure 1. a) Locations of the EEG electrodes. Those retained for synchronization analysis after the decorrelation step are labeled (cf. [10]). Top: forehead, bottom: back of the head. b) Average ERP at PZ. Lower panel: epoch average (mean over subjects) for the control (solid line), semantic incongruity (dashed), and physical mismatch conditions (dotted). Upper panel: corresponding p -values of the difference between an experimental condition and the control condition (pointwise two-sided paired t -test, over subjects). Averages were filtered with a low-pass at 10 Hz and baseline-corrected (300 ms prestimulus).

stimulus presentation, the known N400 component. Distinct from this, the effect of the physical mismatch was found to be a long lasting positivity (250–550 ms). The finding of Kutas and Hillyard was reproduced, namely that a semantic incongruity elicits an N400 component, that is clearly different from the effect of a comparable manipulation regarding the physical properties of the stimulus.

PHASE SYNCHRONIZATION ANALYSIS

To reduce spurious EEG signal correlations due to volume conduction, the spherical spline Laplacian algorithm of Perrin et al. [11] was applied, and subsequently a subset of 27 electrodes was selected for the analysis (see Fig. 1a). A complex Morlet wavelet (center frequency/bandwidth = 7) was used to obtain frequency-specific instantaneous phases $\phi(t, f)$. For each subject, experimental condition, frequency band, and time instant separately, the phases ϕ_{ik} at an electrode $i = 1 \dots N$ of an epoch $k = 1 \dots n$ were taken as input for the phase synchronization analysis, proceeding in following steps:

1) Quantification of the bivariate synchronization strength in each pair of electrodes (i, j) using the measure

$$\bar{R}_{ij} = \left| \frac{1}{n} \sum_k \exp(i \Delta \phi_k^{ij}) \right| \quad \text{where} \quad \Delta \phi_k^{ij} = \phi_{jk} - \phi_{ik}. \quad (1)$$

2) Application of the multivariate analysis algorithm, resulting in a measure of oscillator-to-cluster synchronization strength R_{iC} . This measure quantifies the participation of the respective oscillator (electrode) in the overall process of synchronization. For EEG data, R_{iC} can be displayed as a scalp map to be interpreted as a topography of synchronization. For details see [6].

Figure 2. Time-frequency plots of the measure of overall synchronization, the bivariate mean (Eq. 2). a) Absolute values for the control condition (mean over subjects). Contours are shown for levels 0.15 and 0.2. b) Statistical difference between the semantic incongruity and the control condition, c) between the physical mismatch and the control condition. The difference measure is the pointwise paired t statistic (over subjects); contours indicate the threshold corresponding to a two-sided test at a level of 1%.—Frequencies above 15 Hz were included in the analysis, but there were no statistically reliable effects.

3) To get an overview over the different frequency bands, it is useful to look at time-frequency plots of a measure of overall synchronization. In this paper, we use the *bivariate mean*, the mean of the bivariate synchronization indices over all pairs,

$$\frac{2}{N(N-1)} \sum_{i,j>i} \bar{R}_{ij}. \quad (2)$$

RESULTS

Figure 2a displays the result for the control condition. At frequencies below circa 4 Hz there is a relatively strong sustained synchronization. This is supplemented by a transient increase in overall synchronization around 100–300 ms after stimulus presentation that extends up to circa 10 Hz. There is also a high level of synchronization in the prestimulus interval around 10 Hz that decreases about 300 ms after presentation.

This plot gives a first insight into the frequencies and the time structure of synchronization processes. But from the viewpoint of cognitive science the relevant information is about differences between conditions. The time-frequency plots of Fig. 2b & c represent the statistical difference between the semantic incongruity and physical mismatch conditions, respectively, and the control condition. Taking the displayed contours as an indicator of the relevant time windows and frequency bands, there are three prominent effects related to the experimental manipulations: 1) The semantic incongruity elicits a *decrease* of synchronization at 90–280 ms and 5.7–7 Hz. 2) The physical mismatch elicits an *increase* of synchronization at 0–250 ms and 4–6.3 Hz as well as 3) a second *increase* at 120–270 ms and 8.3–12 Hz.

To determine their scalp distribution, for each of these effects a specific representative time-frequency point was chosen. In Fig. 3, the corresponding statistical difference of

Figure 3. Statistical difference of the synchronization topography between conditions for: a) semantic incongruity vs. control condition at 188 ms and 7 Hz, b) physical mismatch vs. control condition at 128 ms and 5 Hz, and c) physical mismatch vs. control condition at 200 ms and 10 Hz. The difference measure is a statistic based on a pointwise paired permutation test (over subjects); contours indicate the threshold for a two-sided test at levels 5 % and 1 %.

the synchronization topography $\bar{R}_{iC}$ between an experimental and the control condition is shown. The effect of the semantic incongruity (a) can not be attributed to a specific location. For the physical mismatch at 5 Hz (b), there is an increased participation in the left and right temporoparietal areas ($p < 0.01$ at TP7); at 10 Hz (c), an increase mainly in the left parieto-occipital area ($p < 0.01$ at PO3; p -values according to a permutation test [12]).

Additional details are available in the form of a poster presentation [13].

DISCUSSION

The results reported above indicate that ERP average and synchronization analysis deliver comparable but not identical information about the underlying processes. The synchronization indices allow one to observe the modification of the neuronal process that is brought about by the semantic and physical deviations. Similar to the ERP components, the responses to both types of variation are clearly distinct from each other and point to opposite directions, decreased and increased synchronization.

However, because all of the synchronization effects take place *before* those observed in the ERP average, the underlying processes can not be simply identical. While the earliest onset of an ERP component in this experiment takes place at about 250 ms poststimulus, at this time the synchronization effects are almost over. Apparently, with the new analysis method processes are observed that precede and probably prepare for those visible in the averages.

Beyond finding global differences between conditions, for the physical mismatch the multivariate analysis was able to localize the synchronization effects. Their parietal topography fits in with the location of secondary visual cortex areas that can be expected to be involved in the processing of the color change. 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 ERP component.

A study similar in some respects was recently performed by Weiss and Müller; it is not yet published as such, but very briefly described in [14]. The authors auditorily presented German sentences with or without a semantic incongruity, and the EEG record was

processed to obtain a time- and frequency-dependent coherence. They found a decrease in coherence for the semantic incongruity around 30 Hz at 300–500 ms after presentation of the critical stimulus. This finding is materially different from the results obtained by the synchronization analysis presented here: The effect appears at a much higher frequency, and it occurs concurrently to the N400 ERP component. This disagreement may be attributed to some methodical shortcomings of the study of Weiss and Müller. Their experimental design does not include a physical mismatch condition, so that it is impossible to check whether the observed effect is caused specifically by a semantic deviation, and not just by surprise. Secondly, EEG was filtered with an analog band-pass at 0.3–35 Hz before sampling, which is very likely to distort the phase component of the signal. However, from the viewpoint of synchronization theory another explanation is even more likely, namely that the linear coherence measure quantifies a different aspect of the neuronal dynamics than the phase synchronization indices employed here.

In conclusion, phase synchronization analysis has shown to provide information that can be related to the findings of the conventional method, but that goes beyond what has been known before. Its results are of relevance for psycholinguistic theory, because the observation of an effect of the semantic incongruity preceding the N400 suggests that first hints at a semantic processing problem are available significantly earlier than the time window 300–500 ms poststimulus that is currently assumed in the literature [8].

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