# Short-term correlation between frontal and Wernicke's areas during word association: an event-related potential analysis in human subjects

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## Abstract

The aim of this study was to investigate an interaction between frontal and left temporo-parietal cortices in tasks requiring word association. A new method was used to examine averaged event-related potentials in different frequency bands by calculating correlation coefficients between wavelet curves in distant cortical areas. This method was applied to previous event-related potentials recordings which found successive activation of frontal and left posterior areas [1]. Correlated activity at 17 Hz was observed between frontal and left temporal (Wernicke's) areas prior to full activation of Wernicke's area. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

Positron emission tomography (PET) and event-related potentials (ERP) studies have revealed a crucial role for both frontal and temporo-parietal cortices during performance of verbal tasks [1,3,4,13]. The frontal cortex is involved in attention to input and in processing of the input word during generating meanings [3,4,13]. The left temporo-parietal area (Wernicke's zone) may be involved in more complex aspects of the semantics including comprehension of propositions [1,13]. The time course of participation of these areas in the search for word association was reported by Y. Abdullaev and M. Posner [1], who used ERP amplitude analysis: the frontal cortex was activated first at 170 ms after word presentation, and then at 570 ms the left temporo-parietal area was involved. We suggest that these areas are interacting to transmit information related to the required verbal association. Such an interaction should be reflected in synchronization of brain rhythms between these distant cortical regions [9].

The aim of this study was testing a specific hypothesis concerning the interaction between the frontal and the left posterior cortical areas during word association. To test this hypothesis we have analyzed the data set obtained by Y. Abdullaev and M. Posner in order to search for correlated rhythmic activity between the two areas described above.

The experiment was conducted at the University of Oregon and involved 21 right handed subjects (14 females, seven males), aged from 18 to 33.

Single nouns were presented (150 ms on time) on a monitor screen with random intervals of 2–5 s. After 750 ms a response cue (a question mark) appeared for 150 ms. The subject had to either pronounce the word (read a loud task), or supply a semantically related word, e.g. 'hammer-pound' (use-generation task). The subjects performed 120 trials of each type. Before recording each subject had 10–20 practice trials with another set of words.

Electroencephalograph (EEG) was recorded from 64 channels using a right ear mastoid as reference (Fig. 1). Each single EEG trial consisted of a 184 ms baseline recording and 816 ms after the stimulus. EEG was digitized with the rate of 250 Hz after amplification with 0.1–50 Hz band-pass filtering, 3 dB attenuation, and 60 Hz notch filtering.

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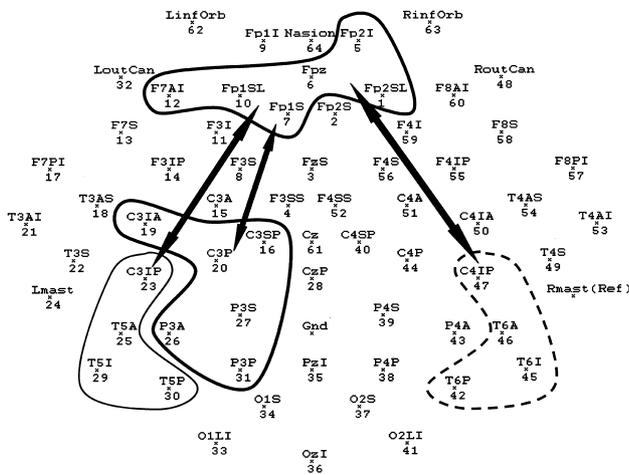*E-mail address:* nikolaev@aha.ru (A.R. Nikolaev).

Fig. 1. The scheme of electrode positions and names. The frontal and left temporo-parietal areas, which activations Y. Abdullaev and M. Posner [1] found in use-generation task with ERP analysis, are indicated by a thick line. The left temporal area, found to interact with the frontal area in this study, is indicated by a thin line. The control right temporal area is indicated by a dashed line. The arrows point to the areas for which correlations of wavelet curves were studied.

The data were recalculated against the average left and right mastoid reference.

The trials with muscle, eye movement and other kind of artifact were excluded from further analysis using the combined method of automatic artifact rejection and visual inspection. One subject was excluded from further analysis because of many artifact channels in the areas of interest.

Since we intended to match our findings with results of analysis of averaged evoked potentials, we could not use coherence as the basis for search of correlated brain activity because this requires single EEG trials to make the calculation. Moreover, Fourier based methods have a poor time resolution in the usual time intervals found in ERP waves and are not adequate for non-stationary signals such as the ERP [14]. So we used a method for estimation of correlated rhythmic activity in distant cortical areas, based on the wavelet transform (WT) of averaged ERP. The WT allows localizing rhythmic trains in the frequency and time domains simultaneously, so it is especially suitable for analysis of short-term ERP rhythmic components [14,16]. WT of a signal is a function of time and is obtained by convolving the original signal with a template. The template is a short complex-valued oscillating signal, called the 'mother wavelet'. By dilating or compressing the mother wavelet it is possible to calculate a WT curve for any frequency. The curve shows the time course of the energy envelope in a band centered around the analyzed frequency. A more detailed review of WT theory and application is given elsewhere [19].

Our goal was to find time intervals of correlated brain activity, i.e. in which the time courses of two WT curves coincided. For this purpose we calculated the correlation coefficient (CC) between the WT curves of a pair of channels. A high value of CC demonstrated that the rhythms of the selected frequency vary simultaneously in the two channels.

It is worth noting that the WT loses information on the fine phase structure of the input signal, but we have previously found that the phase independent estimation of correlation of brain rhythms can provide an effective tool for study not only of averaged ERP but also single trial EEG activity [6–8,11].

The detailed procedure was as follows. The average ERPs were calculated for each subject and task separately. The continuous WT of the ERPs using the Morlet mother wavelet was performed for 19 central frequencies: 9–17, 19, 21, 22, 24, 27, 29, 32, 35, 38, 41, 45 Hz. The frequency step increased with increasing frequency since the frequency resolution of WT decreases with frequency. The time resolution of WT decreased with decreasing frequency, so WT of rhythms below 9 Hz have such poor time resolution they cannot be used for this analysis. For the wavelet type that we used, the bandwidth was 27% and the time resolution was about two periods of the central frequency.

The wavelet curves in certain groups of neighboring channels were averaged to represent the cortical areas described below. For every subject, every mental condition, and every frequency the CCs between WT curves was calculated in a 184 ms (the duration of the prestimulus baseline interval) time window moving along the time axis with 92 ms steps. The CCs were averaged in three bands: alpha 9–13 Hz, beta 15–24 Hz, and gamma 32–45 Hz.

To approximate the normal distribution CCs were z-transformed and then were compared by repeated measures ANOVA. The degrees of freedom in multifactor ANOVAs were corrected using Greenhouse–Geisser procedure. The Duncan's multiple range test was used for post hoc comparisons.

Because the main goal of this work was testing a specific hypothesis of interaction between brain areas, whose activation was revealed by the ERP study [1], we first analyzed the CCs between these locations. The wavelet curves in the frontal (channels 1, 5–7, 10, 12) and left temporo-parietal (channels 16, 19, 20, 26, 27, 31) areas were averaged and CCs for two obtained curves were calculated. ANOVAs with two factors: task (generation versus reading) and time window (nine levels) were performed separately for alpha, beta and gamma bands. Significant effects of time window was found in both alpha $(F_{(8,152)} = 8.9; P < 0.0001)$ and beta $(F_{(8,152)} = 5.6; P = 0.0005)$ bands, but no differences between tasks were found.

However, the previous PET studies of the same task revealed activation of the left parietal and temporal areas that was more lateral than it found in the ERP analysis [15]. Moreover, the projection of Wernicke's zone on scalp is also more lateral [5]. Therefore we calculated the CCs between averaged wavelet curves in the same frontal channels and channels 23, 25, 29, 30 in the left temporal area (Fig. 1). In the beta band (Fig. 2), the ANOVA revealed
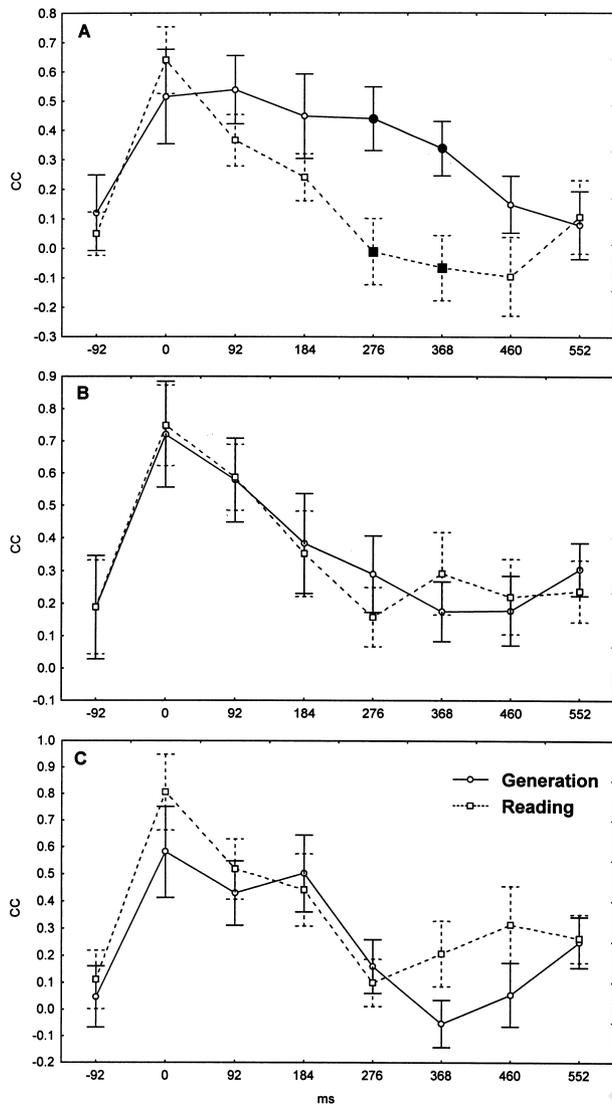
Fig. 2. Correlation coefficients (CC) of wavelet curves in use-generation and reading tasks in the beta band. (A) CCs between the frontal and left temporal (Wernicke's) area. (B) CCs between the frontal and left temporo-parietal area. (C) CCs between the frontal and control right temporal area. The solid points mark the time windows with significant difference between tasks. CCs are plotted against the middles of time windows. Values are mean ± SEM.

significant effect of time window ($F(8,152) = 5.4$; $P = 0.0002$), task ($F(1,19) = 6.52$; $P = 0.019$, and interaction between task and time window ($F(8,152) = 2.1$; $P = 0.04$). Post hoc analysis found that CCs in use-generation were significantly higher in the 184–368 ms ($P = 0.005$) and 276–460 ($P = 0.012$) time intervals, i.e. CCs between wavelet curves in the frontal and left temporal areas increase between 184–460 ms from stimulus presentation. Significant effects of time windows were also found in the alpha band ($F(8,152) = 9.0$; $P < 0.0001$).

As a control location we used an area, which is symmetric to the left temporal area in the right hemisphere (channels 42, 45–47). The ANOVA did not show a task effect, but there was a significant effect of time window in both alpha ($F(8,152) = 9.4$; $P < 0.0001$) and beta ($F(8,152) = 7.3$; $P < 0.0001$) bands.

To study the more detailed spectral structure of CCs inside the beta band we analyzed the CCs for each frequency step (15–17, 19, 21, 22, 24 Hz) in the time interval of 184–368 ms which had the maximal difference between tasks. For the frontal and left temporal areas ANOVA with two factors: task (generation versus reading) and frequency (seven levels) revealed a significant effect of task ($F(1,19) = 8.5$; $P = 0.009$). Post hoc comparison showed the significant increase of CCs in use-generation at 16 Hz ($P = 0.003$), 17 Hz ($P = 0.012$), 19 Hz ($P = 0.027$), and 24 Hz ($P = 0.029$). The maximal $CC = 0.44$ was at 17 Hz. The analysis of CCs between the frontal and left temporo-parietal and the frontal and right temporal areas with the same ANOVA design did not reveal any significant result.

Post hoc analysis of the time window effect is significant in the alpha and beta bands in both tasks between all tested locations due to increasing CCs just after stimulus presentation ($P < 0.001$). Then the CCs returned to the prestimulus level, except between the frontal and left temporal areas in the beta band in use-generation task, as described above. In the gamma band the CCs tended to decrease after stimulus presentation, but this reached significance ($P = 0.05$) only between the frontal and left temporo-parietal areas.

Increases in CCs in both tasks in both alpha and beta bands just after stimulus presentation is evidence of broad-band rhythmic response to sensory stimulation. The response is widespread in cortical areas and so results in high CCs. This widespread correlated activity may be the result of the brain performing integration of distributed sets of neuronal networks spread over multiple cortical areas to produce a coherent representation of a stimulus pattern [10]. This response may consist of superposition of evoked rhythms in several frequencies, which together constitute the compound ERP [2]. However, with increasing frequency, the reactive cortical area becomes more circumscribed and localized, and the duration of EEG reactivity becomes shorter [12]. The phase-locked gamma response to sensory stimulation, which has also been reported [18], is usually not found between distant areas. The broad band sensory response is rather short, and following it, cortical activity becomes more specific and is found in localized narrow band oscillations probably related to more specific cognitive processes.

An increase of correlated brain rhythms at about 17 Hz between the frontal and left temporal areas at 184–460 ms after word presentation may reflect an interaction between these areas during the search for word associations. The beginning of the correlated beta response (184 ms) almost coincides with the start of activation of the frontal area in the previous ERP study (170 ms) [1], but it finishes earlier (460 ms) than the activation of the left temporo-parietal area begins (570 ms). This time course may suggest that the

simultaneous beta response is a sign of information transfer, which serves to initiate cortical activation in the region to which the information is sent, and thus should precede strong activity being found in this area.

The maximum of the correlated response was at 17 Hz. This corresponds to our previous studies [11] and those of other researchers [17,20], which have shown that the EEG synchronization in the beta (13–20 Hz) band is sensitive to the type of cognitive operation involved. In addition, coherence in the 13–18 Hz has been found to reflect semantic difference between concrete and abstract words [21].

Synthesizing the results of our frequency analysis and the previous ERP amplitude studies of the same data [1], one may hypothesize the following course of search for word associations. First, stimulus presentation results in short-term phase-locked activity widespread in cortical areas in broad frequency bands. In both use-generation and reading tasks this is manifested in appearance of early ERP components and in high CCs in alpha and beta bands in a number of areas. This widespread effect lasts 170 ms. This time might be considered as a interval needed for an object to be consciously perceived [7]. Afterward the more specialized and local information processing begins. At about 170 ms frontal areas become active. These areas are involved in attention and analysis of the input item during use generation. Almost at the same time (at 184 ms) the interaction between the frontal and the left temporal (Wernicke's) area starts at about 17 Hz. This interaction lasts to 460 ms and leads to activation of a large area of the left temporo-parietal cortex manifested in increase of ERP amplitude at 570 ms. This simultaneous beta response between the two areas occurs earlier than the ERP amplitude changes. This may be that information transfer results in activation of a distant cortical area. The activation of the left temporo-parietal region is probably associated with the integration of related word meanings required to obtain the use of the lexical stimulus [1,13].

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