Cerebral Information Transfer During Word Processing: Where and When Does It Occur and How Fast Is It?

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Abstract: Different regions of the brain have to interact to perform language processing. Such neural integration processes can be studied by measuring synchronization of oscillations. Coherence is the best known algorithm to study synchronization between two sites of the cortex with regard to selected oscillation frequencies. Phase coherence quantifies phase synchronization, in particular. In addition, cross phase (or simply phase) gives information about the direction and speed of the spread of oscillations. We use a new method to study short-time phases between different sites of the cortex in order to explore transient neural networks during word processing. Particularly, processing of abstract and concrete nouns was investigated by dynamic phase analysis of the alpha1 frequency band (8–10 Hz). Abstract and concrete nouns turned out to induce different dynamic networks of information transfer. Whereas processing of concrete nouns excites a widespread network for about 800 msec, the interhemispheric interactions during abstract noun processing are restricted to 300–500 msec after word presentation. Further, the direction of cerebral information transfer differs for the two word categories. Additionally, it could be shown that the propagation speed of information is slower for concrete nouns than for abstract nouns. *Hum. Brain Mapping* 19:18–36, 2003. © 2003 Wiley-Liss, Inc.

Key words: EEG coherence and phase; directed information transfer; dynamic networks; synchronization; oscillation; propagation speed; word processing; abstract and concrete nouns; language

INTRODUCTION

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Language processing represents a complex cognitive act, which is performed in different structures of the brain. Thereby, the brain's work is not only restricted to the activity of circumscribed and specialized brain areas. In order to maintain intact and efficient language processing, different neural networks have to interact mostly over short time intervals. Therefore, transient "functional language centers" are generated, executing different tasks dependent on their specific demands [Weiss et al., 2000]. Word processing in particular comes along with activity within characteristic networks of neurons transiently linked

by dynamic connections [Pulvermüller et al., 1995, 2000].

In this study, the formation of dynamic networks of information transfer during processing of different word categories, namely abstract and concrete nouns, is investigated. Previous studies [Weiss et al., 2000; Weiss and Rappelsberger, 1996] pointed at the existence of different functional networks involved whilst processing these word categories. Whereas widespread networks are occupied whilst processing concrete nouns, fewer language-specific networks take part whilst processing abstract nouns. In addition to the investigation of such specific networks of brain activity, the temporal properties of information transfer during word processing are of interest.

Oscillatory synchronization is being explored as a possible mechanism for the interaction of neural assemblies. Most studies have employed EEG coherence to investigate oscillatory synchrony. Novel methodical approaches [Arnold et al., 1998; Schack et al., 1999] allow the calculation of coherence with high time resolution and overcome the requirement of stationarity of signals. However, although coherence may be understood as a measure of phase stability [Nunez et al., 1997], it does not specifically quantify phase-relationships. Recently, several measures were developed to measure phase synchrony between brain signals [Lachaux et al., 1999; Rodriguez et al., 1999; Rosenblum et al., 1996; Tass et al., 1998; Varela et al., 2001]. An alternative approach is, thus, the direct estimation of phase delays yielding results on the direction and speed of information propagation. The time delay derived from the phase delay hints at the direction of information propagation between signals recorded from different sites within a given frequency band. Further, the value of the phase delay allows to determine the speed of information transfer. In this study, we used a novel approach to estimate phase delays between two EEG signals continuously over time [Schack et al., 1999]. This method allows the investigation of the stability of phase delays over a set of trials and participants for each time point. Thus, pathways, direction, and speed of information flow shall be compared between abstract and concrete noun processing.

In this study, the investigation of synchronous oscillators is focused on the lower alpha-frequency band (8–10 Hz) where power spectra for 23 participants at almost all electrode positions show a clear peak at 9 Hz. Besides, Klimesch et al. [1996] showed that alpha frequency is correlated with the speed of information processing, as measured by reaction time. Moreover, prior coherence studies resulted in increased values

for the lower alpha band during auditory word processing in comparison with the rest situation [Weiss and Rappelsberger, 1998].

MATERIALS AND METHODS

Experiment

Twenty-three female German native speakers (23.8 years old, SD 2.7; monolingual; right-handed) participated in the experiment. They had to memorize four auditorily presented word lists, each containing either 25 concrete or 25 abstract nouns. The presentation of word lists was separated by four resting periods when people were instructed to relax silently and were prevented from hearing any extrinsic stimulus.

One hundred disyllabic nouns were equated for frequency of occurrence and ranked on a 12-point scale based on a corpus of about 10 million words [Meier, 1967]. Concrete nouns showed an average of 6.49 ± 2.80 , abstract nouns 4.61 ± 1.73 . *T*-tests yielded no significant word frequency difference between abstract and concrete nouns. Furthermore, nouns were matched on imageability and concrete-/abstractness due to studies of Mitterdorfer [1976], Baschek et al. [1977], and Offe et al. [1981]. Both samples of concrete and abstract nouns, respectively, used in this study differed significantly for the variables “imagery” and “concrete-/abstractness” (*t*-test, 2 *P* ≤ 0.0001).

Nouns spoken by a female voice and digitized at 22 KHz were presented via computer, HiFi-amplifier, and headphones. They had a mean articulatory duration of 0.76 ± 0.12 sec and were presented to the subjects with a stimulus onset asynchrony of 2.5 sec.

The 19-channel EEG was recorded according to the international 10-20 system against the average signals of both ear lobes ((A1+A2)/2). EEG was recorded during memorization of the different lists of nouns and during four interspersed resting periods with eyes opened lasting 1 min each. The electrooculogram (EOG) was recorded from two electrodes at the left lateral outer cantus and above the right eye. The sampling frequency was 256 Hz. Electrode impedance did not exceed 8 k ω ; and signal bandpass was 0.3–35 Hz. After recording, EEG data were screened for artifacts by visual inspection. Only artifact free trials (around 45 for both abstract and concrete nouns) were included in further analysis.

Data analysis

An adaptive estimation method of coherence and cross phase functions is used, which allows high time

and frequency resolution. The basic idea of the method is as follows: a pair of EEG channels is understood as a two-dimensional stochastic signal process. This process is modeled as a two-dimensional autoregressive moving-average (ARMA) model with time-dependent parameters. The optimization criterion for adapting parameters is the minimization of the prediction error of the model in the least mean square sense. The correction of the model according to this criterion is performed at every sample point. Thus, the parameters of the model are functions of time and allow the parametric calculation of the momentary spectral density matrix of the ARMA model, which approximates the spectral density matrix of the underlying pair of EEG channels for the momentary time-point t .

$$\hat{\mathbf{S}}_t(f) = \begin{pmatrix} \hat{S}_{11,t}(f) & \hat{S}_{12,t}(f) \\ \hat{S}_{21,t}(f) & \hat{S}_{22,t}(f) \end{pmatrix} \quad (1)$$

where $\hat{S}_{11,t}(f)$ and $\hat{S}_{22,t}(f)$ are the autospectra and $\hat{S}_{12,t}(f)$ and $\hat{S}_{21,t}(f)$ are the cross-spectra for the momentary time-point t . The interested reader can find the detailed estimation procedure in Schack et al. [1999]. Subsequently, the continuous estimations of coherence and cross phase are derived from the momentary spectral density matrix of the fitted ARMA model.

$$\hat{\rho}_t^2(f) = \frac{|\hat{S}_{12,t}(f)|^2}{\hat{S}_{11,t}(f) * \hat{S}_{22,t}(f)} \quad (2)$$

$$\hat{\phi}_t(f) = \arg\{\text{Re}(\hat{S}_{12,t}(f)) + i \cdot \text{Im}(\hat{S}_{12,t}(f))\}, \quad (i = \sqrt{-1}). \quad (3)$$

The cross phase is often simply called “phase” and represents the phase difference for the correspondent frequency component of two EEG signals. Therefore, the phase may be used for the calculation of the time shift between two signals. The time delay τ in [msec] for frequency component f is determined from the phase ϕ given in [rad] by

$$\tau[\text{ms}] = \frac{1000 \cdot \phi[\text{rad}]}{2\pi f} \quad \text{with} \quad \phi[\text{rad}] = \phi[^\circ] \frac{2\pi}{360}. \quad (4)$$

The coherence is symmetrical with respect to the order of the channels

$$\hat{\rho}_{12,t}^2(f) = \frac{|\hat{S}_{12,t}(f)|^2}{\hat{S}_{11,t}(f) * \hat{S}_{22,t}(f)} = \frac{|\hat{S}_{21,t}(f)|^2}{\hat{S}_{11,t}(f) * \hat{S}_{22,t}(f)} = \hat{\rho}_{21,t}^2(f),$$

whereas the cross phase is anti-symmetrical with respect to the order of the channels:

$$\begin{aligned} \hat{\phi}_{12,t}(f) &= \arg\{\text{Re}(\hat{S}_{12,t}(f)) + i \cdot \text{Im}(\hat{S}_{12,t}(f))\} \\ &= \arg\{\text{Re}(\hat{S}_{21,t}(f)) - i \cdot \text{Im}(\hat{S}_{21,t}(f))\} \\ &= -\hat{\phi}_{21,t}(f). \end{aligned}$$

If $\hat{\phi}_{12,t}(f) > 0$, channel 2 takes the leading position and channel 1 the trailing position. For a chosen frequency band $[f_{\text{low}}, f_{\text{upper}}]$ band coherence and cross phase for any arbitrary electrode pair (i,j) may be calculated as functions of time:

$$(\hat{\rho}^2)^{(i,j)}_{[f_{\text{low}}, f_{\text{upper}}]}(t) \quad \text{and} \quad (\hat{\phi})^{(i,j)}_{[f_{\text{low}}, f_{\text{upper}}]}(t) \quad (5)$$

For the estimation of mean coherence and phase values in multi-trial studies and ingroup studies averaging procedures have to be performed. The mean value of instantaneous coherence for M trials will be calculated for every sample point:

$$\hat{\rho}_t^2(f) = \frac{1}{M} \sum_{m=1}^M \hat{\rho}_{t,m}^2(f) \quad (6)$$

where $\hat{\rho}_{t,m}^2(f)$ denotes the instantaneous coherence at sample point t for the frequency f of the m -th trial, $m = 1, \dots, M$. In case of phases, it must be noticed that phase values are defined in the interval $[-180 \text{ degrees}, 180 \text{ degrees}]$. If the phase values accumulate in the neighborhood of the saltus ± 180 degrees, averaging of the phase values may result in an erroneous low mean value. To avoid this, the coordinates on the unit circle are averaged and phase angle is obtained from the mean coordinates:

$$\begin{aligned} \hat{\xi}_t(f) &= \frac{1}{M} \sum_{m=1}^M \cos \hat{\phi}_{t,m}(f) \\ \hat{\eta}_t(f) &= \frac{1}{M} \sum_{m=1}^M \sin \hat{\phi}_{t,m}(f) \\ \hat{\phi}_t(f) &= \arg \frac{\hat{\eta}_t(f)}{\hat{\xi}_t(f)} \end{aligned} \quad (7)$$

where $\hat{\phi}_{t,m}(f)$ denotes the instantaneous phase at sample point t for the frequency f of the m -th trial, $m = 1, \dots, M$.

Mean coherence estimation according to Equation (6) is based on single trial coherences. Phase variability among trials is not taken into consideration. Phase variability for each time point may be quantified by instantaneous phase coherence. Instantaneous phase coherence is derived from the mean coordinates of phase on the unit circle:

$$\begin{aligned}\hat{\kappa}_t(f) &= \sqrt{\hat{\xi}_t^2(f) + \hat{\eta}_t^2(f)} \\ &= \sqrt{\left(\frac{1}{M} \sum_{m=1}^M \cos \hat{\phi}_{t,m}(f)\right)^2 + \left(\frac{1}{M} \sum_{m=1}^M \sin \hat{\phi}_{t,m}(f)\right)^2}.\end{aligned}\quad (8)$$

Coherence, phase, and phase coherence were investigated for all possible 171 electrode pairs of the 19-channel EEG during 1,000-msec epochs of word processing beginning with word onset. All further examinations were made for the alpha1 frequency band: $[f_{\text{low}}, f_{\text{upper}}] = [8 \text{ Hz}, 10 \text{ Hz}]$. Averaging was performed within the α_1 -band over adjacent spectral lines with frequency resolution of 0.5 Hz. For each trial, 256 instantaneous coherence and phase values were obtained. The next step was averaging of coherence and phase over the single trials time point by time point according to Equations (6–7) and the calculation of phase coherence for the set of trials according to Equation 8. For data reduction, the 1,000-msec trials were divided into ten sections of 100 msec each. Averaging over the time points within the sections yielded 10 values for coherence, phase, and cross phase per presentation mode. The pooled instantaneous coherence and phase values across subjects are derived from the average of the mean coherence and phase values of the individuals.

The stochastic distributions of instantaneous coherence and phase described above are unknown. In order to obtain non-zero coherences, 95%-quantiles are determined for uncorrelated noise processes in dependence on the trial number M . The quantiles found serve as thresholds for non-zero instantaneous coherence. Additionally, in order to ensure non-zero coherent relationship, coherence $\hat{\kappa}_{XY}(f)$ was estimated for each electrode pair on the basis of the Fourier transform and compared statistically with zero [see e.g., Schack et al., 1999]. For this aim, Fisher's z -transform $\hat{Z}_{XY}(f) = \arctanh[\hat{\kappa}_{XY}(f)] = 0.5 \times \ln(1 + |\hat{\kappa}_{XY}(f)|)/(1 - |\hat{\kappa}_{XY}(f)|)$ yields a normally distributed random variable with variance $\text{Var}[\hat{Z}_{XY}(f)] = 1/\nu$, where the number of degree of freedom is obtained from the number

of trials. Thus, coherence is different from zero (significance level 5%) if $\hat{Z}_{XY}(f) > u_{0.05} \cdot \sqrt{1/\nu}$, where $u_{0.05}$ is the 95%-quantile of the normal distribution.

In the case of an unstable phase relation between two EEG signals, the phase is distributed uniformly in the interval $[-180 \text{ degrees}, 180 \text{ degrees}]$. A non-zero stable phase relation with respect to a certain time interval was established by comparing the mean phase values of the participants with zero using one-sample t -tests. Statistical comparison between mean phase values and phase coherence values of the participants for different tasks was performed by means of the Wilcoxon test for paired samples.

RESULTS

Motivation for the Choice of the Alpha1 Frequency Band

The calculation of phase for a certain frequency between signals of two sites of the cortex presupposes the existence of oscillations with this frequency at both locations with a high signal-to-noise ratio. This precondition may be proven by the inspection of mean power spectra and coherence. Figure 1 shows the grand mean of the power spectra during processing of abstract (gray curves) and concrete (black curves) nouns.

The power spectra show a clear peak appear around 8–10 Hz in power spectra for both tasks at all electrode positions. The resting condition exhibits peaks in the power spectra around 8–10 Hz at all electrode positions as well, and additionally at 10.5 Hz at the parietal electrode positions P3, Pz, P4.

A further requirement for the investigation of phase relations is the difference of coherence from zero. For each electrode pair and each participant, the mean time course of lower alpha coherence was calculated according to Equation 6. A threshold for non-zero coherence derived from the 95%-quantile of coherence values of two independent noise processes. The comparison with this threshold yielded non-zero coherence for all electrode pairs for both the resting periods and the processing of abstract and concrete nouns. The same result was found for coherence estimations based on Fourier transform. Coherence values (8–10 Hz) were different from zero with a significance level of 5% for all electrode pairs for both the resting periods and the processing of abstract and concrete nouns.

Figure 1.

Grand mean of power spectra for 23 participants for abstract (gray curves) and concrete (black curves) noun processing. The power spectra were calculated for 1,000-msec intervals starting with the word onset.

Dynamic pathways and direction of information transfer

Coherence may be understood as a measure of goodness of information transfer. Coherence different from zero hints at some interaction between two sites of the brain with regard to a certain frequency. However, computation of coherence mixes up amplitude and phase information of both signals and is not sufficient to get explicit information about phase-locking phenomena between two oscillators. In order to examine information transfer on the basis of synchronized oscillations, cross phases or phase differences, respectively, were examined according to Equation 3.

A uniform phase difference between two EEG records across all single tasks expresses a directed information transfer between these two sites of the brain. A phase relation between two sites of the cortex is called stable, if there exists a determined direction of information transfer for all participants. A uniform direction of information transfer was proven by one sample *t*-tests (see *Materials and Methods*).

In a first step, stable phase relations during rest were explored. On average, 27 EEG epochs of 1,000 msec length were used per participant. The observation of stable phase relations within consecutive 100-msec intervals of the 1,000-msec resting period yielded approximately the same result with only weak variations. The resulting network of mean stable phase relations for 23 participants during the resting condition (over the whole period of 1,000 msec) is shown in Figure 2.

Since participants received no auditory extrinsic stimuli, this pattern of stable phase relations hints at a general cortical pattern of information transfer even at rest. The Fz plays a decisive role as trailing position; additional important trailing positions are Cz, T3, and T4. In general, information transfer is mostly directed from posterior to anterior sites. Moreover, the right hemisphere exhibits more stable phase relations than the left and there is much more information transfer from the left to the right hemisphere.

In order to follow the highly dynamic process of word processing, the time interval of 1,000 msec beginning with word presentation was subdivided into 10 segments of 100-msec length. For each time segment, the presence of a stable phase relation was investigated for all electrode pairs. Figure 3 shows the results for memorizing the abstract nouns.

The partition of the 1,000-msec time interval into 100-msec segments reveals a dynamic network changing over time. The most dense web of intra- and interhemispheric stable phase relations appears in the time intervals 300–400 and 400–500 msec. The

Figure 2.

Network of stable phase relations across 23 participants during rest separated for interhemispheric, and right and left hemispheric electrode positions. For each participant, phases were calculated from about 27 EEG epochs of 1,000-msec length each. The arrows point from leading to trailing electrode positions.

dense network of information transfer between the left and the right hemisphere collapses after 600 msec. As for interhemispheric phase connections, there is a general tendency from posterior parts of the left hemisphere to the right hemisphere. As for intrahemispheric phase relations, and beginning with 200 msec, the network of phase relations is stronger on the left hemisphere. The right hemisphere shows fewer stable phase relations and, thus, less information transfer. Further, the main role of Fz as trailing position is noteworthy.

The dynamic networks of stable phase relations for concrete nouns are presented in Figure 4.

Figure 3.

Dynamic networks of information transfer derived from 23 participants whilst abstract noun processing. Starting with word onset, networks of stable phases are illustrated within ten consecutive 100-msec intervals.

Figure 4.

Dynamic networks of information transfer derived from 23 participants whilst concrete noun processing. Starting with word onset, networks of stable phases are illustrated within ten consecutive 100-msec intervals.

TABLE I. Number of Stable Phase Relations, in Total There Are 171 Possibilities, for 23 Participants During Word Processing (one sample t-test for comparing phase values with zero)

	msec									
	0–100	100–200	200–300	300–400	400–500	500–600	600–700	700–800	800–900	900–1,000
Abstract nouns	37	22	45	65	62	47	47	41	38	46
Concrete nouns	50	58	85	87	87	86	90	87	78	67

Again, most interhemispheric phase connections from the posterior parts of the left hemisphere are directed towards the right hemisphere. Yet, on the frontal and temporal regions, no preferred direction can be seen. Moreover, the web of stable inter- and intrahemispheric phase relations is much denser than with abstract nouns. It appears at 200 msec and holds on up to 800 msec. Just as for abstract nouns, Fz plays a main role as trailing position. In contrast to abstract nouns, there are several long-distant intra- and interhemispheric relations with O2 as leading position. The intensity of the web scarcely diminishes at the end of the 1,000-msec interval.

Obviously, the network of information transfer is more widespread for concrete nouns. This result coincides with the observation of West and Holcomb [2000]. They noticed that concrete words elicit more negative event-related potentials (ERPs) than abstract words between 300 and 800 msec. Just as in our study, this effect was widespread across the scalp. For a comparison of the dynamics and intensity of activated brain webs for abstract and concrete nouns, the number of stable phase relations are listed in Table I.

For abstract nouns, the period of intense information transfer is concentrated around 300–400 msec after word onset. In contrast to this effect, limited in time, for concrete nouns the period of most intense information transfer comprises a large time interval between 200 and 800 msec. These different temporary properties of the interhemispheric phase networks are shown in Figure 5.

The role of particular electrodes as leading or trailing positions may be established by counting the number of stable leading or trailing phase with respect to a certain electrode position. A mapping procedure of these numbers offers the topography of leading and trailing positions. Figure 6 shows the sequences of maps with a time resolution of 100 msec of the weight of leading positions (first and third rows) and trailing positions (second and fourth rows).

For abstract nouns (Fig. 6, top first row), the number of leading positions is increased in the time interval from 300 to 600 msec. As shown above, the intensity of

the phase network is pronounced in this time interval. Further, a lateralization to the left posterior hemisphere may be observed. Fz is a main trailing position for the whole time. The main information transfer in the time interval from 300 to 600 msec leads to the frontal areas. Later on, the central position Cz and centroparietal position Pz also take over trailing positions. The map sequences of leading and trailing positions for concrete noun processing (Fig. 6, bottom two rows) are different. A dense phase network appears between 200 and 800 msec. Here, O2 plays a main role as leading position. The trailing positions are prevalent in the whole frontal area with their center at Fz. Again, the general direction of phase shifts goes from posterior to anterior areas.

Speed of information transfer

The investigation of phases enables the analysis of the propagation speed of information in addition to the direction of information transfer. According to Equation 4, phase values can be converted into time delays (in ms) and yield a measure for the propagation of alpha waves between two sites.

In order to get a global overview, electrode pairs were ordered according to their distance and subdivided

Figure 5.

Amount of stable interhemispheric phase relations. The number of stable interhemispheric phase relations are presented in 100-msec steps for abstract and concrete noun processing, starting with word onset.

Figure 6.

Leading and trailing positions of information transfer. The map sequences illustrate the topography of weighted leading and trailing positions for abstract (top) and concrete (bottom) noun processing with a time resolution of 100 ms. The first and third rows show maps of weighted leading positions, the second and fourth rows show maps of weighted trailing positions.

vided into seven classes (see Table II). Further, only stable phase values were taken into consideration.

Absolute phase delays are listed in Table II (left). The delay values of the rest situation in general coincide with the results of other authors [Nunez et al., 1997, 2001; Nunez, 2000; Thatcher et al., 1986]. Nunez et al. [2001] showed that phase velocities match cortico-cortical propagation velocities. Delays in cortico-cortical propagation were explained by finite propagation speed of action potentials. The authors found delays in the range of 6–14 m/sec. Burkitt et al. [2000] investigated phases of steady-state visual-evoked potentials (SSVEP) and detected evoked traveling waves with estimated phase velocities ranging from 7 to 11 m/sec. Phase delays found in our study range around

10 m/sec. Additionally, it was shown, that phase delays and, consequently, propagation speed depend on the cognitive task. For concrete noun processing, the delays are generally larger than during rest. On average, whilst abstract noun processing the delays are larger than during rest too, however, the difference is not so clear.

Direct comparison between abstract and concrete noun processing yields significantly larger delays for concrete nouns except for the class of electrode pairs with the largest distance, possibly due to the low number of stable phase relations. These findings point at the activation of a more widespread network of neurons and distributed pathways during concrete noun processing.

TABLE II. Absolute Phase Delays (in msec) and Significant Differences Between Lower Alpha Oscillations for All Electrode Pairs Ordered by Electrode Distance

Electrode distance (cm)	Absolute phase delays (msec)			Significant differences (<i>P</i> values)		
	Abstract nouns	Concrete nouns	Rest	Abstract vs. concrete nouns	Concrete nouns vs. rest	Abstract nouns vs. rest
5.5–7.5	4.35	6.48	5.68	0.000	0.024	0.083
8–9	7.08	8.37	6.88	0.026	0.094	0.784
10–14	8.90	12.57	7.72	0.005	0.001	0.153
15–18	13.19	16.34	8.79	0.003	0.000	0.005
19–21	13.62	19.65	14.75	0.001	0.021	0.563
22–25	21.22	24.54	14.40	0.004	0.000	0.026
26–36	33.52	31.31	29.78	0.394	0.605	0.171
All electrode pairs	14.25	16.88	11.73	0.000	0.000	0.011

* Significant differences (*P* values of the Wilcoxon tests for paired samples) with respect to the tasks (right side). The *P* values in bold satisfy the multiple significance level of 5% following the Bonferroni-Holm correction.

Phase variability

Cross phase was used to describe pathways and directions of information transfer. The strength of phase synchronization or phase variability will be compared by instantaneous phase coherence according to Equation 8. As with the analysis of cross phase, the time interval of 1,000 msec beginning with noun processing was subdivided into 10 segments of 100-msec length. Mean phase coherence values were calculated for each segment and all electrode pairs for abstract and concrete noun processing. Additionally, mean phase coherence values for the rest situation were determined. Figure 7 gives an overview on the comparison of phase coherence values between word processing and rest (Fig. 7A), and between abstract and concrete noun processing (Fig. 7B) (5% significance level).

For both abstract and concrete (Fig. 7A) noun processing, the number of significant differences in phase coherence is higher than at rest, beginning at 200 msec after the word onset up to the end. This means, phase variability among the trials decreases rapidly during word processing. These results hint at the generation of functional pathways during word processing. The phase network for concrete noun processing turned out to be more strongly synchronized than for abstract noun processing.

The comparison of phase coherence values between abstract and concrete noun processing (Fig. 7B) yields specific phase networks up to 600 msec. From 600 up to 1,000 msec, the phase network is much stronger for concrete noun processing. Figure 8 reveals the different topographies of phase networks. (Figure 8 should be compared with the results in Fig. 7.)

Beginning with 200 up to 600 msec, higher phase coherence values are found within the left hemisphere for abstract noun processing (Fig. 8, dashed lines) and within the right hemisphere for concrete noun processing (Fig. 8, solid lines). Stronger widespread phase synchronization appears for concrete noun processing beginning from about 600 msec. These observations of phase variability emphasize and complete the results concerning phase networks based on stable direction of information transfer.

DISCUSSION

The results of the present study suggest that word categories such as abstract and concrete nouns exhibit different networks of dynamic information transfer, which differ in both their topography and their temporal sequence. In addition, the direction of information transfer and the propagation speed differ between abstract and concrete nouns.

The pattern of stable phase relations during the resting condition may reflect a general cortical pattern of information transfer without any specific ex- and intrinsic stimulation. This basic pattern of cortical information transfer in the lower alpha band may be interpreted in terms of sustained attention, which provides the basis for the efficiency of more complex aspects of attention and cognitive processes [Sarter et al., 2001]. Furthermore, the higher amount of stable phase relations within the right hemisphere correlates with anatomical and physiological findings showing more long-range fibers and fewer cells in the right than in the left hemisphere, especially at frontal regions [Gur et al., 1980]. The prominent role of Fz as trailing position may be correlated with the impor-

A

B

Figure 7.

The number of significantly different phase coherence is presented in 100-ms steps starting with word onset (Wilcoxon test for paired samples). **A:** Abstract noun processing vs. rest and concrete noun processing vs. rest. Black marker indicate number of higher phase coherence for word processing, gray marker indicate number of higher phase coherence for the rest situation. **B:** Abstract vs. concrete noun processing. Black marker indicate number of higher phase coherence for concrete noun processing, gray marker indicate number of higher phase coherence for abstract noun processing.

tance of the frontal cortex during rest ("hyperfrontality") [Hagstadius and Risberg, 1989]. Moreover, it corresponds with findings that frontal regions favor long-range processing, while posterior regions are more involved in local processing [Thatcher et al., 1986]. However, since the role of Fz as main trailing position is also evident during linguistic processing, this pattern of phase relations may also reflect the importance of the frontal cortex as a mnemonic controlling and

filtering system for extrinsic and intrinsic sensory stimuli.

Most interestingly and, in contrast to the phase pattern in the resting condition during linguistic processing, most stable phase relations are found in the left hemisphere, which is known to house a higher number of neuronal structures relevant for language processing. Moreover, essential differences in the amount and the temporal and spatial distribution of the networks of phase relations are found for abstract and concrete nouns.

One of the main findings concerns the difference of the time window of most intense information transfer for abstract and concrete nouns. Whereas abstract nouns exhibit the most dense network of intra- and interhemispheric stable phase relations between 300 and 500 msec after stimulus onset, the most dense network for concrete nouns appears within 500 and 800 msec. This finding implies that the most intense information transfer in the brain is found about 300 msec earlier for abstract nouns than for concrete nouns. It seems that processing concrete nouns lasts longer and the most intense information transfer occurs somewhat later than during abstract noun processing. These results can be explained by the multimodal nature of the concrete concepts, which elicit more (and multimodal) associations and, in particular, mental images. This higher-level process takes some time to develop [Kosslyn, 1988], and probably takes place mainly within the time interval of 500 and 800 msec [West and Holcomb, 2000].

In general, concrete nouns exhibit more stable phase relations and, thus, increased information transfer than abstract nouns, especially, within the right hemisphere and between both hemispheres. More intense participation of the right hemisphere during concrete nouns than during abstract noun processing has been shown by several authors [e.g., Jessen et al., 2000; Villardita et al., 1988; Volf and Razumnikova, 1999]. The most pronounced difference between abstract and concrete nouns within each hemisphere is mainly found between 200 and 400 msec. This effect may coincide with the so-called N400 ERP-component (see Appendix B), which is larger for concrete nouns and commonly occurs between 300 and 500 msec after stimulus onset [e.g., Kutas and Van Petten, 1988]. Our results fit well into the general finding that activity within this time interval is correlated with the concreteness effect and semantic integration during word processing.

Concerning the number of stable interhemispheric phase relations, abstract and concrete nouns show different temporal properties. Between 100 and 300

Figure 8.

Differences in phase coherence between abstract and concrete noun processing derived from 23 participants. Starting with word onset, results of statistical comparison (Wilcoxon test for paired samples, 5% significance level) are illustrated for ten consecutive

100-msec intervals. Electrode pairs with higher phase coherence for concrete noun processing are connected with solid lines, electrode pairs with higher phase coherence for abstract noun processing are linked with dashed lines.

msec and between 400 and 1,000 msec after stimulus onset, concrete nouns exhibit a higher number of interhemispheric stable phase relations, with a maximum between 500 and 800 msec. In contrast, abstract nouns show more stable phase relations between hemispheres and, thus, more dense information transfer between 300 and 400 msec. In this time window, mutual exchange of information between left and right hemispheric resources seems to be more important for abstract nouns than for concrete nouns. Maybe the brain tries to improve the efficiency of semantic integration for abstract nouns by increasing access to right hemispheric resources within this time interval.

A further important result concerns the direction of information transfer between both hemispheres. Concrete nouns exhibit a dense net of stable interhemispheric phase relations, which shows information transfer both from left to right hemispheric sites and vice versa. On the other hand, abstract nouns display mainly information transfer from the left to the right hemisphere. To the best of our knowledge, this is the first time to show differing direction of information transfer between hemispheres for different word categories. It may be that, whilst concrete noun processing, left and right hemispheric resources mutually exchange and update information. However, during abstract noun processing information comes mainly from the left hemisphere, maybe using the right hemisphere only as a kind of temporary buffer but not using specific right hemispheric information (except in the time interval 300 and 400 msec, see above).

The global direction of information processing within and between hemispheres goes from posterior to anterior sites. Concerning the electrodes, which fulfill the role of main leading positions, abstract nouns show left-lateralized posterior parietal leading positions whereas concrete nouns display several right-lateralized posterior leading positions with O2 as the main leading position. Furthermore, the role of Fz as main trailing position during processing of both abstract and concrete nouns is noteworthy. Whereas abstract nouns only show Fz and later in time Cz and Pz as trailing positions, concrete nouns exhibit mainly additional trailing positions distributed bilaterally at anterior sites (Fp1, Fp2, F3, F4, F7, F8). The increased participation of the right occipital lobe and the two frontal lobes during processing concrete nouns fits well to the findings on visual mental imagery. On the one hand, visual imagery is performed by the same neuronal structures, which also support visual processing and perception [Farah, 1989]. On the other hand, it has been hypothesized that the activation of the left inferior prefrontal cortex may reflect a "mental

imagery subsystem," responsible for holding mental images in semantic working memory [West and Holcomb, 2000]. During concrete noun processing, mental images are likely to be held in working memory, which is one strategy to memorize them more efficiently. These findings support the existence of additional memory systems for concrete nouns and thus support the dual-coding model or an extended version of this model [Holcomb et al., 1999; Paivio, 1991] rather than the context availability approach [Schwanenflugel and Shoben, 1983].

Another interesting finding concerns the significant difference in the speed of information transfer between abstract and concrete noun processing. Although concrete nouns are, in general, processed more quickly in reaction time studies [Eviatar et al., 1990], this does not necessarily allow conclusions on the speed of processing within the brain. One reason may be that most reaction time studies use lexical decision tasks where participant have to decide whether words are real words or non-words. This task does not activate the whole semantic "range" or concrete nouns but is only necessary for classifying a word as a real word or a non-word. In the case of concrete nouns, under most circumstances, this process is faster. In the present study, participants had to memorize nouns, which activated distributed, polysynaptic neuronal networks. During memorizing concrete nouns far more semantic associations are elicited (e.g., visual mental images) comprising the activity of distributed sensory and motor regions. The slower activation of such distributed networks may explain the slower propagation speed for the concrete nouns.

CONCLUSIONS

To summarize, with the calculation of phase relations, new information on word processing is obtained. Beside the demonstration of different pathways of information transfer, abstract and concrete noun processing show a difference in the direction and speed of information transfer. As shown in a previous study [Weiss and Rappelsberger, 1996], concrete nouns are processed in more widespread and dense neural networks within the brain. For the first time it is shown that information transfer is slower for concrete nouns possibly due to multiple resources used, and that the direction of information transfer between hemispheres differs for word categories. Furthermore, the time interval of most intense information transfer occurs later during concrete noun than abstract noun processing.

The results of this study demonstrate that the analysis of quickly changing networks of information transfer is possible on the basis of instantaneous phase estimation.

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APPENDIX A: EXPLANATION OF THE METHOD

The adaptive estimation procedure of instantaneous coherence was conducted in two steps as follows: the first step was the adaptive fitting of a linear model to a pair of EEG channels.

Let $\mathbf{x} = \{(\mathbf{x}_i^1 \mathbf{x}_i^2)^T\}_{i=0,1,2,\dots}$ be the sample values of two channels of an EEG record, where $(\mathbf{x}_i^1 \mathbf{x}_i^2)^T = \begin{pmatrix} x_i^1 \\ x_i^2 \end{pmatrix}$ and i denotes the number of the sample value. This two-dimensional EEG signal was fitted by a two-dimensional autoregressive moving average (ARMA) model with time-varying parameters:

$$\mathbf{y}_n + \sum_{k=1}^p \mathbf{A}^k(n) \mathbf{y}_{n-k} = \mathbf{z}_n - \sum_{j=1}^q \mathbf{B}^j(n) \mathbf{z}_{n-j}, \quad (\text{A1})$$

where n is the n -th time point t_n , p and q are the orders of the model, $\mathbf{z}$ is a two-dimensional independent white noise process, $\mathbf{y}$ is the two-dimensional model process, and $\mathbf{A}^k(n)$ and $\mathbf{B}^j(n)$ are 2×2 -matrices of the autoregressive and moving average parameters. The minimisation of the momentary quadratic prediction error of the model leads to the following adaptive estimation procedure for the parameter matrices:

$$\begin{aligned} \hat{\mathbf{A}}^k(n) &= \hat{\mathbf{A}}^k(n-1) - c_n \mathbf{e}_n \mathbf{x}_{n-k}^T; \quad k = 1, \dots, p \\ \hat{\mathbf{B}}^j(n) &= \hat{\mathbf{B}}^j(n-1) - c_n \mathbf{e}_n \mathbf{e}_{n-j}^T; \quad j = 1, \dots, q \end{aligned} \quad (\text{A2})$$

where $\{\mathbf{e}_n\}_{n=1,2,\dots}$ is the estimated vector sequence of the prediction error:

$$\mathbf{e}_0 = 0$$

$$\mathbf{e}_n = \mathbf{x}_n - \mathbf{y}_n$$

$$= \mathbf{x}_n + \sum_{k=1}^p \hat{\mathbf{A}}^k(n-1) \cdot \mathbf{x}_{n-k}^T + \sum_{j=1}^q \hat{\mathbf{B}}^j(n-j) \cdot \mathbf{e}_{n-j}^T. \quad (\text{A3})$$

The algorithm (A2)–(A3) is a generalisation of the LMS algorithm for adaptive filtering of one-dimensional signals by autoregressive models for the case of adaptive filtering of multidimensional signals by autore-

gressive moving-average models. The time-varying stepwidth c_n was chosen reciprocally proportional to the sum of momentary variances of the two EEG signals. This signal-dependent determination of the stepwidth c_n guarantees the stability of the adaptive estimation procedure. The model order (p , q) was established in accordance with the Hannan information criterion [Hannan and Kavalieris, 1984].

The second step of the adaptive estimation procedure consists of the parametric calculation of the spectral density matrix for each sample point. The momentary transfer function $\mathbf{H}_n(f)$ of the fitted ARMA model may be calculated by the formula

$$\mathbf{H}_n(f) = \mathbf{A}_n^{-1}(f) * \mathbf{B}_n(f), \quad (\text{A4})$$

with the momentary parameter matrices

$$\mathbf{A}_n(f) = \mathbf{I} + \sum_{k=1}^p \hat{\mathbf{A}}^k(n) e^{-ikf} \quad \text{and}$$

$$\mathbf{B}_n(f) = \mathbf{I} - \sum_{j=1}^q \hat{\mathbf{B}}^j(n) e^{-ijf}. \quad (\text{A5})$$

The momentary covariance matrix $\mathbf{S}_n$ of the bivariate prediction error $\{\mathbf{e}_n\}_{n=1,2,\dots}$ may also be estimated in an adaptive manner according to:

$$s_{ij}(0) = 0$$

$$s_{ij}(n) = s_{ij}(n-1) - c_s \cdot (s_{ij}(n-1) - \mathbf{e}_n^i \cdot \mathbf{e}_n^j), \quad i = 1, 2; \quad n = 1, 2, \dots, \quad (\text{A6})$$

where c_s is a constant with $0 < c_s < 1$. It is now possible to calculate the spectral density matrix at every sample point n by

$$\mathbf{S}_n(f) = \mathbf{H}_n(f) * \Sigma_n * \mathbf{H}_n^{*T}(f), \quad (\text{A7})$$

where $\mathbf{H}_n^{*T}(f)$ denotes the complex conjugate and transpose of $\mathbf{H}_n(f)$. This means that this adaptively estimated spectral density matrix

$$\mathbf{S}_n(f) = \begin{pmatrix} S_{11,n}(f) & S_{12,n}(f) \\ S_{21,n}(f) & S_{22,n}(f) \end{pmatrix}$$

is a function in frequency and in time. In such a way, we obtain the instantaneous quadratic coherence func-

Figure 9.

Coherence and cross phase estimations for simulated signals. **Signal x, Signal y:** Simulated signals $x(n)$ and $y(n)$ (see text). **Instantaneous coherence:** Time course of instantaneous coherence (black curve) calculated according to (A8) and coherence estimation based on the Fourier transform (gray step function) for

the time intervals $\{0-2 \text{ sec}\}$, $\{2-4 \text{ sec}\}$, $\{4-6 \text{ sec}\}$, $\{6-8 \text{ sec}\}$. **Bottom:** Time course of instantaneous cross phase (black curve) calculated according to (A9) and cross phase estimation based on the Fourier transform (gray step function) for the time intervals $\{0-2 \text{ sec}\}$, $\{2-4 \text{ sec}\}$, $\{4-6 \text{ sec}\}$, $\{6-8 \text{ sec}\}$.

Figure 10.
Grand mean (23 subjects) of evoked potentials for abstract nouns (gray) and concrete nouns (black).

tion and instantaneous cross phase function at every sample point:

$$\hat{\rho}_n^2(f) = \frac{|S_{12,n}(f)|^2}{S_{11,n}(f) * S_{22,n}(f)}. \quad (\text{A8})$$

$$\hat{\phi}_n(f) = \arg\{\text{Re}(\hat{S}_{12,n}(f)) + i \cdot \text{Im}(\hat{S}_{12,n}(f))\}, (i = \sqrt{-1}). \quad (\text{A9})$$

For demonstrating the temporal properties the following simulation was performed:

$$x(n) = \begin{cases} \xi(n); 1 \leq n < 1024 \\ \sin(9 \cdot n) + \xi(n); 1025 \leq n < 2048 \\ \xi(n); 2049 \leq n < 3072 \\ \sin(9 \cdot n) + \xi(n); 3073 \leq n < 4096 \end{cases}$$

$$y(n) = \begin{cases} \eta(n); 1 \leq n < 1024 \\ \sin(9 \cdot n + 63^\circ) + \eta(n); 1025 \leq n < 2048 \\ \eta(n); 2049 \leq n < 3072 \\ \sin(9 \cdot n - 63^\circ) + \eta(n); 3073 \leq n < 4096 \end{cases}$$

Thereby $\{\xi(n)\}$ and $\{\eta(n)\}$ are uncorrelated Gaussian noise processes, the sampling frequency was set 512 Hz. Signals are illustrated in Figure 9 (top two panels).

Figure 9 (Instantaneous coherence) shows the time course (black) of instantaneous coherence for the frequency band (8–10 Hz) calculated according to eq. A8 (or eq. 2). The coherence estimations based on the Fourier transform is presented as a step function (gray) for

the four signal intervals {0–2 sec}, {2–4 sec}, {4–6 sec}, {6–8 sec}. The time course of instantaneous cross phase for the frequency band (8–10 Hz) calculated according to eq. A9 (or eq. 3) is illustrated in Figure 9 (bottom panel). Again, the cross phase estimations based on the Fourier transform is presented as a step function (gray) for the four signal intervals {0–2 sec}, {2–4 sec}, {4–6 sec}, {6–8 sec}. For the second time interval {2–4 sec} and the third time interval {4–6 sec}, both instantaneous coherence and cross phase vary around the values of the Fourier estimations. For time intervals with two uncorrelated noise processes, instantaneous coherence yields small values (excluding for the beginning {0–0.3 sec} where the model starting with zero model parameters has to adapt) whereas instantaneous cross phase takes random values.

APPENDIX B: EVENT-RELATED POTENTIAL

The grand-mean ERPs time-locked to the onset of abstract and concrete nouns are plotted in Figure 10.

Concrete nouns elicited a more negative ERP than abstract nouns between 300 and 600 ms after stimulus onset, especially at frontal and central sites. Significant differences were predominantly found in the time window between 350 and 550 ms, peaking around 400 ms (Wilcoxon test, significance level 5%). This concreteness N400 effect coincided temporally with the classic N400 component, which commonly was correlated with semantic integration processes. [e.g., Holcomb et al., 1999; Kutas and Van Petten, 1988].