Theta synchronization predicts efficient memory encoding of concrete and abstract nouns

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Functional and topographical differences between processing of spoken nouns which were remembered or which were forgotten were shown by means of EEG coherence analysis. Later recalled nouns were related with increased neuronal synchronization (= cooperation) between anterior and posterior brain regions regardless of presented word category (either concrete or abstract nouns). However, theta coherence exhibited topographical differences during encoding of concrete and abstract nouns whereby former were related with higher short-range (mainly intrahemispheric), later with higher long-range (mainly interhemispheric) coherence. Thus, theta synchronization possibly is a general phenomenon always occurring if task demand increases and more efficient information processing is required. Measurement of EEG coherence yields new information about the neuronal interaction of involved brain regions during memory encoding of different word classes. *NeuroReport* 11:2357–2361 © 2000 Lippincott Williams & Wilkins.

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INTRODUCTION

Human cognitive information processing require the integrated action of multiple brain areas distributed throughout both cerebral hemispheres [1]. Distributed cell assemblies are activated simultaneously during basic perceptual processes as well as during complex cognitive functions, such as language and memory. The cooperation of such cell assemblies is probably revealed by similarity of temporal patterns, which has been studied in animals [2] and in humans (for review see [3]). These patterns of electrical cooperativity are highly complex and differ according to task demands. This so-called temporal synchronization of neuronal activities during various cognitive tasks can be studied in the frequency domain by calculating coherence between EEG signals [4].

The coherence function is a frequency-domain measure of similarity between EEG signals. The signal content of two recordings may change considerably with time. Particular frequencies may change their amplitude, new frequency components may add up into the signals and relative phase between components in the two channels may alter. Moreover, noise (in the sense of uncorrelated activity of neuronal assemblies) in one or both channels may occur. The calculation of coherence provides an analytical tool by which these changes between signals can be monitored and quantified in the frequency domain. Thus, coherence between two EEG signals is a measure of phase stability and reflects the degree of functional cooperation between neuronal substrates underlying the generation of those signals.

EEG coherence or synchronization during cognitive processes in healthy humans has been increasingly studied during recent years [3–7]. However, only a few studies of the relationship between EEG coherence and memory have been performed up to now [8–11]. Generally, during usage of distinct types of memory, these studies reported an increase of synchronization within different frequency bands between brain regions involved in the respective task. Interestingly, these distinct types of memory (working memory, episodic encoding and associative learning) were correlated with findings within different frequency bands. However, the most common frequencies associated with memory processes lay within the classical theta range (~4–7 Hz). An increase of theta power or coherence was related with working memory demands [10] and episodic memory encoding [12,13]. In particular, increased theta coherence between anterior and posterior brain regions correlated with visual working memory [10] and successful encoding and storage of concrete episodic information [11,14]. However, increased theta long-range fronto-parieto-occipital coherence was also observed in subjects performing better in an intelligence test [15]. Therefore it may be hypothesized that anterior-posterior theta coherence represents a general prerequisite for many types of efficient information processing rather than mere memory processing and that the theta band is predominately challenged if there is need for efficient processing of (difficult) tasks. This corresponds with the fact that theta synchronization was also found during selective attention, associative information processing, oddball tasks, orienting and other cognitive tasks (for reviews see [16,17]).

In the present study we concentrated on the investigation of the theta band during memory encoding of spoken concrete and abstract nouns. We expected higher theta band coherence for recalled nouns independent of the word category investigated. Furthermore, we assumed higher coherence for abstract nouns than concrete nouns since the theta band commonly reflects task difficulty and it is known that abstract nouns are more difficult to encode, store and retrieve [18].

MATERIALS AND METHODS

Twenty-three female students (aged 19–30, mean age 23.6 years) participated in the experiment. They all were right-handed and monolingual with German as their native language. Fifty concrete and 50 abstract German nouns constituted the stimuli for this study. They were matched on word frequency, imageability and concreteness/abstractness (for further details see [7]). Nouns were presented auditorily to the participants via computer, HIFI-amplifier and HIFI-headphones. They were spoken by a female voice and were digitized (22 kHz) and edited by computer. Words had a mean articulatory duration of 0.76 ± 0.12 s and were randomly presented to each subject with a stimulus onset asynchrony of 2.5 s. Four different blocks with 25 randomized nouns each were presented in random order across the experiment separated by short resting periods. Participants had to memorize the nouns and immediately after the presentation of each list they were asked to recall the words previously encoded. On average 9 ± 1.73 concrete and 6 ± 1.23 abstract nouns out of 25 words of each list were recalled per subject. Recalling of concrete nouns was significantly better than recalling of abstract nouns (paired t-test, $2p \leq 0.0001$).

EEG was recorded with 19 electrodes (10/20 system) against the averaged signals of both earlobes ((A1 + A2)/2). Signal band-pass was 0.3–35 Hz and data were digitally sampled at 256 Hz. After recording, EEG data were screened for artefacts (eye blinks, horizontal and vertical eye movements, muscle activities) by visual inspection on a monitor and on paper.

EEG data were obtained during the memory encoding of the different lists of nouns and were later divided into EEG epochs of subsequently recalled and of not recalled nouns. This was done separately for concrete and abstract nouns. The beginning of each noun was marked by a trigger and the following 1 s EEG epoch was Fourier-transformed. Then, for each subject averaged power spectra for all 19 electrode positions and cross-power spectra between all possible electrode pairs, which yielded 171 values per frequency, were computed (for further methodological explanations see [4]). To reduce the large data set adjacent spectral values were averaged to obtain broad band parameters for the following frequency bands: delta-1 (1–2 Hz), delta-2 (3–4 Hz), theta (5–7 Hz), alpha-1 (8–10 Hz), alpha-2 (11–12 Hz), and beta-1 (13–18 Hz). In the current study we restricted the presentation of our findings on the theta band since it has frequently been demonstrated that, especially, this band correlates with memory processes [10,13,17]. Normalization of the 171 cross-power spectra yielded 171 coherence values for the theta band. Finally, grand mean values were obtained by averaging coherence values across subjects.

RESULTS

Repeated-measures ANOVA was performed on Fisher-z-transformed coherence values during abstract and concrete noun processing for the theta band. Findings for other frequency bands during processing auditory and visual concrete nouns were presented and discussed elsewhere [11]. In the present paper we concentrate on the difference in memory encoding in the theta band for abstract and concrete nouns. The factors and their levels were memory (recalled *vs* not recalled), type (concrete *vs* abstract) and scale (short-range *vs* long-range coherence). Coherence was classified as short-range if it was calculated between adjacent electrodes. It was classified as long-range if at least one electrode was situated in between. Results for the theta band are presented in Table 1.

One main result is the significant main effect of the factor memory. Inspection of the respective means reveals significantly higher mean coherence during memory encoding of recalled than of not recalled nouns independent of word category. The significant two-way interaction between memory and scale indicates the difference between recalled and not recalled nouns to be much more pronounced for long-range coherence than short-range coherence (Fig. 1).

The significant main effect for the factor scale indicates that short-range coherence values are generally higher (mean squared coherence 0.563) than long-range coherence values (mean squared coherence 0.194) and mainly underlines the fact that scalp coherence generally decreases with increasing electrode distance (Table 1).

In order to obtain topographical information about single coherence differences between either recalled or not recalled nouns we applied paired Wilcoxon tests separately for concrete and abstract nouns. Results were converted to error probabilities and presented as lines between the electrodes in schematic drawings of the brain (see Fig. 2). This statistical procedure has to be considered as a statistical filter and the obtained error probabilities are purely descriptive. They hint at possible spectral parameter differences between selected tasks existing over the multiple comparisons.

Table 1. Repeated measures ANOVA: main effects and interactions for coherence values

Memory (recalled/not recalled), F (1, 22)	11.7**
Type (concrete/abstract), F (1, 22)	0.0
Scale (short-/long-range), F (1, 22)	5303.3***
Memory × Type, F (1, 22)	0.4
Memory × Scale, F (1, 22)	12.2**
Type × Scale, F (1, 22)	8.2**
Memory × Type × Scale, F (1, 22)	3.2

*** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$.

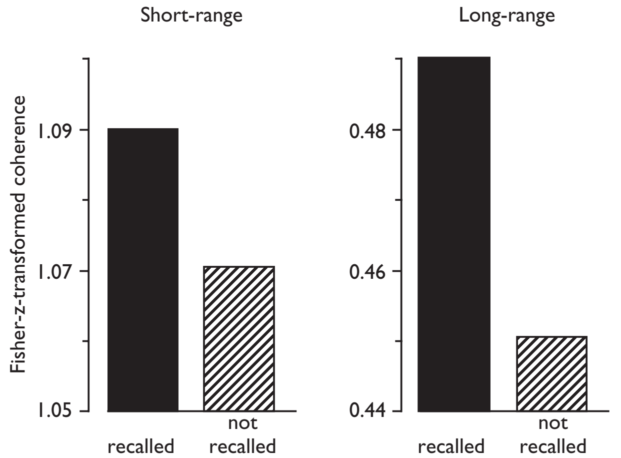

Fig. 1. Mean coherence difference between recalled and not recalled nouns dependent on electrode distance. Short-range coherence was calculated between adjacent electrodes, long-range coherence between distant electrodes with at least one electrode in between (note different scale).

Generally, as revealed by ANOVA, recalled nouns elicit higher coherence than not recalled nouns as well for concrete as for abstract nouns. However, the topography of coherence differences is partly distinct between these word groups. Both recalled abstract and concrete nouns show increased coherence between frontal (F1, F7) and temporo-occipital (T5, O1) sites within the left hemisphere. Abstract nouns elicit additional coherence increase between T3 and posterior sites. Moreover, concrete nouns elicit networks of additional short-range coherence differences between frontal/temporal and central/parietal sites. Concrete words show a similar pattern of coherence differences between recalled and not recalled nouns within the right hemisphere whereas abstract nouns show almost no differences. Interhemispheric coherence differences are found mainly frontally and anterior temporally for concrete nouns. In contrast, abstract recalled nouns differ from not recalled ones in showing clearly higher coherence between anterior and posterior temporal sites and between left frontal and right posterior sites (T4, T6, P4, O2).

Word category differences between concrete and abstract nouns, which are independent whether nouns are recalled or not are reflected by the ANOVA two-way interaction between type and scale (Table 1). This significant interaction results from the fact that short-range coherence is higher for concrete nouns whereas long-range coherence shows the opposite (Fig. 3).

DISCUSSION

Two major results were obtained in the present study: at first, the theta band reflected higher coherence during the encoding of later recalled nouns, independent of word category. This difference depended on electrode distance, namely was more pronounced for long-range coherence. However, the topography of this overall higher coherence was slightly different for concrete and abstract nouns. Secondly, significant word category differences were demonstrated and also depended on electrode distance. Whereas concrete nouns showed higher short-range coher-

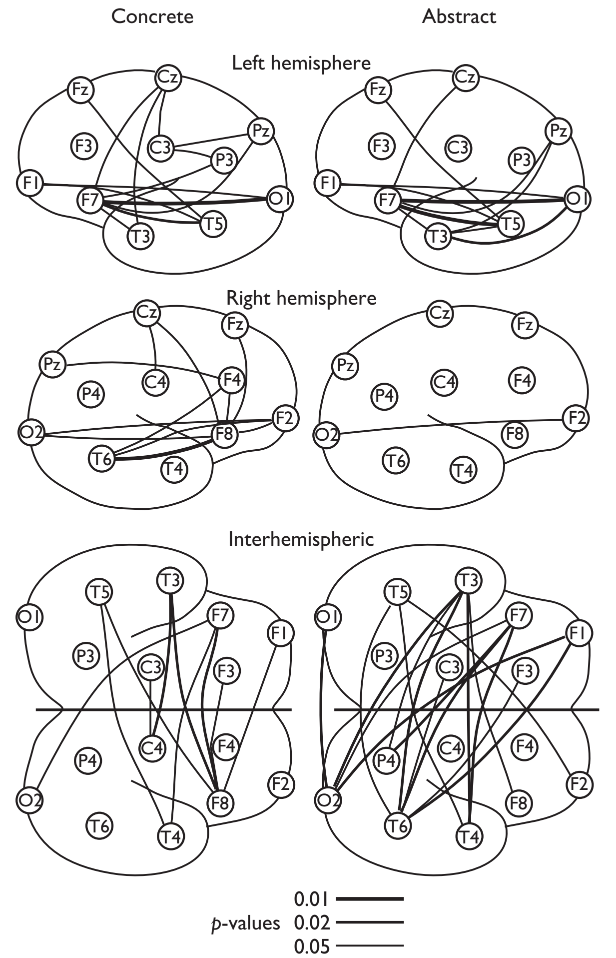

Fig. 2. Coherence differences (left, right and interhemispheric) between recalled and not recalled nouns, separately for concrete and abstract nouns. Paired Wilcoxon-tests were used as statistical filters and the resulting error probabilities were mapped onto schematic brain maps as connecting lines between the electrodes involved. Lines between respective electrodes demonstrate higher coherence for recalled nouns compared with not recalled ones.

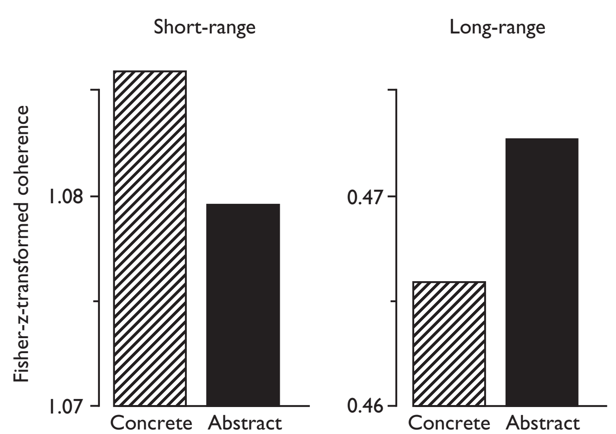

Fig. 3. Mean coherence difference between concrete and abstract nouns separately for short- and long-range coherence (see Fig. 1).

ence abstract nouns correlated with higher long-range coherence.

We found that theta synchronization was consistently higher during episodic memory encoding of later recalled nouns regardless if concrete or abstract nouns were presented. Especially, coherence between long-range left frontal and temporo-parieto-occipital activities increased and reflected the extensive cooperation between these regions during the memory encoding of later recalled nouns. This was probably related with two aspects of verbal memory encoding, namely the encoding and maintenance of phonological representations of the words [19] and the semantic encoding which predominately is performed within left prefrontal regions [20]. Our findings support the current opinion concerning memory operations [21]. Memory networks are distributed, widely spread over the cortex and overlap each other. These hierarchical organized systems are highly interactive comprising cortical neurones, which can be part of many different neuronal assemblies (networks) and consequently also part of different memory systems [21]. The widely distributed memory systems have to cooperate in the dynamic organisation of information processing within large-scale cortical networks. This dynamic cooperation is commonly performed within narrow frequency bands and thus the pattern of interacting neuronal structures can be distinct dependent on the frequency band investigated. Concerning memory operations, thalamic, non-thalamic (e.g. hippocampal) and cortical sources (e.g. prefrontal, posterior parietal cortex) are part of these networks [1] and it was suggested that hippocampal–cortical pathways induce synchronous theta oscillations which entail a cooperation of the respective memory systems [10,13,17]. As for our results later recalled nouns were related with an increased cooperation between left prefrontal and posterior (temporal, parietal and occipital) sites. Prefrontal cortex is an executive part of the working memory system [21], which interacts with temporal regions, involved in the sensory processing of the stimuli, and parieto-occipital association areas. A significant enhancement of theta coherence between prefrontal and posterior electrodes was recently reported during visual working memory [10].

As for memory encoding of concrete and abstract nouns the pattern of higher theta synchronization was slightly different. Whereas the left hemisphere did not reflect striking differences memory encoding of later recalled concrete nouns was related with intrahemispheric coherence increase within the right hemisphere. The synchronization patterns resembled the patterns of the left hemisphere. Moreover, during processing of concrete nouns enhanced synchronization between left fronto-temporal and right frontal regions occurred whereas during abstract nouns processing right posterior temporo-parietal and left frontal and anterior-temporal sites enhance their exchange of information. Right hemispheric participation during processing concrete nouns has been shown frequently [14,22,23]. However, during successful memory encoding of concrete nouns the interaction between both hemispheres was not so important as during processing of abstract nouns. Instead, synchronization within each hemisphere was more pronounced for concrete nouns. Thus, both hemispheres enhanced the interaction between anterior and posterior brain regions but they did it relative independently. That means that more or less independent left and right hemispheric networks were activated during the successful encoding of concrete nouns.

During the encoding of abstract nouns the left hemispheric synchronization networks were supported by the right hemisphere but there was no additional independent network within the right hemisphere. Since memorizing of abstract nouns is more difficult and could not be performed as successful as memorising of concrete nouns an increased support of right hemispheric resources seems plausible. Significant activation of right hemispheric structures during the processing of abstract words was also recently demonstrated using fMRI [24]. Nevertheless in our study, an additional independent right hemispheric synchronization network during successful encoding of abstract nouns, which was comparable to the pattern during successful encoding of concrete nouns, was missing. This may be one reason for the greater vulnerability of abstract nouns for loss or disturbance [6] and thus their significantly worse recall [18]. During encoding of concrete nouns independent right hemispheric resources are activated whereas during encoding of abstract nouns the right hemisphere indeed interacts with the left hemisphere but this cooperation seems to lack efficiency.

The significant interaction between word category and electrode distance revealed that concrete nouns exhibited higher short-range coherence whereas abstract nouns were correlated with higher long-range coherence. This effect expressed the difference in encoding of these two word types independent if words were recalled later on or not. Previous studies have shown that processing of concrete nouns elicited increased synchronization between a higher amount of distributed brain regions compared to abstract nouns. This was due to the multimodal nature of concrete nouns, the increased elicitation of semantic associations during the encoding phase [6] and thus a larger distinctiveness of concrete words [25]. However, in the present study concrete nouns indeed showed higher short-range coherence which fitted to the previous findings but abstract nouns exhibited higher long-range coherence which predominately resulted from higher interhemispheric synchronization. This higher long-range synchronization may reflect the brain's attempt to integrate encoding of abstract nouns into a large-scale network, which should prevent their loss and ensure better retention. We speculate that this process often fails due to the lack of semantic features of abstract nouns.

Thus the theta band reflected the difference between encoding of later recalled or not recalled nouns and also reflected a difference between the encoding of distinct word categories independent whether they were recalled or not. A frequent occurrence of theta coherence increases over long distances was often observed during more complex cognitive tasks [3,10] and was even related to better performance in an intelligence test [15]. Possibly, theta oscillations, especially, in long-range fronto-parieto-occipital networks are a general phenomenon, always occurring if more efficient information processing is required and task demand increases. Semantic associations and semantic memory encoding of concrete and abstract nouns were previously described to be reflected mainly within higher frequencies such as 10–12 Hz [13,26] or 13–18 Hz [6], whereas episodic memory encoding and retrieval was found to be correlated with frequencies within the theta range (4–7 Hz) [12,13]. As for our findings of previous studies and the results of the current study we found different frequency bands during verbal memory encoding each reflecting different subcomponents of the entire cognitive process. Thus, we are in accordance with the opinion of Basar *et al*. [16], who stated that 'it is impossible to assign a single function to a given type of oscillatory activity'. According to their hypothesis every complex and integrative brain function is manifested in the superposition of several oscillations.

CONCLUSION

EEG coherence in the theta band (4–7 Hz) reflected the difference between successfully and not successfully encoded words. In addition, it also reflected a difference in strategies during encoding of word categories independent whether the words were recalled or not. Memory encoding of later recalled nouns was related with enhanced coherence or synchronization whereas encoding of later not recalled nouns lacked interaction between respective brain regions. Especially, synchronization between distant frontal and temporo-parietal brain regions within the left hemisphere increased in relation to synchronization between adjacent brain regions. The overall better recalling of concrete nouns may be based on the efficient use of more or less independently acting networks of both hemispheres. Recalled abstract nouns were processed mainly within left hemispheric networks with increased support of the right hemisphere. However, due to the lack of semantic features the brain's attempt to successfully encode, store and retrieve abstract concepts often fails. EEG coherence improves our knowledge about the functional participation of more or less independently working neuronal networks during verbal memory encoding and allows to decide whether a word is likely to be recalled or not.

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