Event-related theta activity reflects memory processes in pronoun resolution

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A recent eye tracking study reported a reverse effect of a noun's lexical frequency in the context of the resolution of coreferring pronouns. Investigating the neurophysiological basis of this effect, the present electroencephalogram study found differential patterns in theta activation when participants read pronouns referring to nouns of different frequency classes. Evoked theta power after pronoun onset increased with the frequency of the critical noun. This finding suggests differential load on memory resources depending on the nouns' frequency. Elevated attention promoting memory encoding for low-frequency words is assumed to facilitate the resolution of pronouns. Location of sources of differential theta activity in the parahippocampal region is accounted for by its role in an association network that mediates memory processes. *NeuroReport* 00:000–000 © 2006 Lippincott Williams & Wilkins.

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Introduction

Imagine a reader being confronted with a sentence such as: *John plucks the BLOSSOM from the elder tree since he plans to give it to Mary as a Valentine's gift.* Could there be any reason why the task of reading the pronoun *it*, which refers back to the second noun phrase (NP), takes less time than interpreting the pronoun *it* in another sentence such as this: *John plucks the FLOWER from the elder tree since he plans to give it to Mary as a Valentine's gift* [1]? Is it plausible to assume, as proposed by Pynte and Colonna [2], that the reader has less difficulties to process the coreferential relation between the noun and the pronoun when the latter refers back to a low-frequency word such as *blossom* rather than to a word such as *flower*, which occurs approximately 10 times more often in natural language?

At first glance, this speculation runs counter to the so-called *word-frequency effect* that refers to the observation that the processing of low-frequency words typically involves higher processing costs compared with high-frequency words, as revealed by longer reaction or reading times and/or higher error rates in a variety of language-related tasks. A recent eye-tracking study, however, suggests that a reverse word frequency effect might occur in the context of pronominal resolution [1]. The authors report shorter reading times in a sentence reading task for pronouns that refer back to low frequency as compared with high-frequency nouns. Van Gompel and Majid's [1] results contradict Simner and Smyth's [3], who propose that no effects of the antecedent's relative frequency should be found during pronominal processing.

As the processes underlying the resolution of coreferential pronouns, that is, of pronouns referring back to linguistic items already mentioned in a given sentence, are of central importance to psycholinguistic theory [4], Heine *et al.* [5] conducted an event-related potentials (ERPs) study to resolve the issue of whether and how the relative lexical frequency of a noun influences the resolution of coreferential pronouns. Using nouns of three different frequency classes, the authors found systematic P300 amplitude effects for pronouns, with largest P300 amplitudes following the presentation of pronouns referring back to low-frequency nouns, and smallest amplitudes for the high-frequency condition.

The generally accepted interpretation of the P300 is that this component reflects cognitive processes of stimulus evaluation and recognition. It, however, remains a matter of debate whether the P300 is an indicator of an updating of internal representations when stimulus information requires the revision of a memory trace, that is, context updating [6], or whether, as the alternative view holds, the P300 represents processes of informational closure when input characteristics are in accordance with expectations, that is, context closure [7].

This ambiguity in interpreting P300 effects does not allow for a deeper understanding of the functional significance of the amplitude differences reported by Heine *et al.* [5]. Following other research groups (e.g. [8]), Heine *et al.* [5] suggest further investigations into these ERP effects by means of time–frequency analyses of the electroencephalogram (EEG) data. In their seminal study, Hagoort and his colleagues [8] have demonstrated that analyses in the time–frequency domain may be the means to gain further insights into underlying functional principles that determine the generation of ERPs. All the more so because ERP compo-

nents such as P300 have been shown to be generated by superposition of activity in different frequency bands owing to stimulus-locked phase resetting processes [9,10].

The fact that a number of studies have demonstrated that the amplitude of the P300 varies as a function of load on short-term memory resources is of special interest for the present research question. Over a wide range of memory-related tasks, it was shown that P300 amplitude decreases when load on the system increases [6,11]. It might thus prove fertile to investigate activation changes in those frequency bands of the human EEG that are discussed in the literature as indicators of memory-related processes to gain further insights into the functional significance of P300 amplitude effects in pronoun resolution, that is, primarily event-related changes of activation in the lower frequency bands of the whole EEG spectrum [12].

It has been shown that event-related shifts of activity in each frequency band of the EEG can be further differentiated into two different types of signal changes. Evoked activity, on the one hand, is both time and phase-locked to the onset of a given stimulus event, whereas induced responses are nonphase-locked and reflect general amplitude changes in rhythmic background activity. Although induced activity contributes crucially to event-related electrophysiological responses in the later time windows, phase-locked activity dominates the signal for a short period after stimulus presentation [12]. Thus, Doppelmayr and colleagues [13] showed that for the first 400 ms of the post-stimulus interval, theta band power consists of a large part of strictly phase-locked activity. It can be assumed, as demonstrated by several research groups (e.g. [8,14]), that The lower frequency ranges of the EEG spectrum evoked activity in the early time window exhibits the same functional characteristics as parameters of whole band power, which consists of both evoked and induced activity.

To gain insight into memory-related processes that may underlie the P300 amplitude effects reported by Heine *et al.* [5], analyses of evoked responses in the theta band were conducted in the present study. The main question was whether shorter reading times [1] are reflected in time–frequency EEG measures that are known to be sensitive to differential load on memory resources.

Materials and methods

For the present study, 25 sets of EEG data from Heine *et al.* [5] were subjected to time–frequency and source-localization analyses. In the original study, 27 right-handed individuals (seven men, mean age 22.8 years, SD=4.65) participated after informed consent. All participants were native German speakers and had normal or corrected-to-normal vision.

Experimental stimuli consisted of 150 paired sentences, of which the first sentence contained a NP and the second a pronoun referring back to this NP (Table 1). The head noun of each NP belonged to one of three word frequency classes (high, middle, low) according to the CELEX German database [15]. The nouns in the three experimental conditions did not differ significantly with respect to word length. Relevant semantic variables such as concreteness, animacy, and emotional valence were controlled by constructing triplets of quasi-synonymous words containing one word from each frequency class.

On the basis of these matched nouns, triplets of paired sentences were constructed that were identical with respect to syntactic and semantic structure, and the relative positions of nouns and pronouns across the frequency classes. Ambiguity in pronoun reference was avoided using syntactic gender and number agreement. The occurrences of different pronoun forms were matched for the three conditions. Words preceding the critical pronouns were identical for the sentences of each triplet.

The 150 sentence pairs were presented visually in a word-by-word format on a computer display in randomized order. A fixation marker appeared in the middle of the screen for 300 ms before sentence presentation. Each word of the paired sentences was presented in the middle of the screen for 400 ms (interstimulus interval: 300 ms). Between trials, a blank screen appeared for 2000 ms. No filler items were included. Verification questions (yes/no) appeared 300 ms after the sentence presentation. Participants were instructed to read the stimuli silently and respond to the questions by button press. Answering these questions required the participants to establish the correct relations between the pronouns and the nouns.

Continuous EEG was recorded from 27 Ag/AgCl scalp electrodes placed according to the international 10–20 system. Electrooculogram was monitored. Electrodes were online referenced to linked mastoids. Impedances were kept below 5 kΩ for the EEG and below 10 kΩ for the electro-oculogram. The sampling rate was 250 Hz.

EEG waveforms were filtered (bandwidth: 0.1–30 Hz, 24 dB/oct) and controlled for artifacts using an automatic rejection procedure (cutoff: ±40 μV). Only artifact-free trials were included in the data set. The remaining trials (67%) were evenly distributed across all conditions. The continuous EEG was segmented into single trials, time-locked to the presentation onset of the critical pronouns in the sentences (intervals: −500 to 700 ms and −300 to 700 ms). The data of three participants had to be excluded from further analyses owing to insufficient numbers of artifact-free EEG segments.

The time signal of each EEG segment was decomposed into its time–frequency representation by means of the S-transform [16,17]. The S-transform can be considered a highly efficient and flexible short-time Fourier transform that allows for the use of frequency-adjusted analysis windows over the whole frequency range without being restricted by the admissibility condition, as is the case with the wavelet transform. Furthermore, the S-transform is directly linked to the Fourier transform as averages over time provide the Fourier spectrum.

Evoked power (−500 to 700 ms) was calculated at frequencies f from 0.1 to 20 Hz (0.8 Hz steps), using a Gaussian window (SD σf) with a constant ratio $f/\sigma f=7$ (such a window type is called Morlet window in the context wavelet analysis). At 6 Hz, for instance, this corresponds to a window length comparable to a Hann window of about 875 ms [17].

Topographical two-dimensional scalp maps were acquired by means of analyses of channel data in the theta-frequency band using the topoplot-function of the open source EEGLAB toolbox (A. Delorme and S. Makeig, Swartz Center for Computational Neuroscience, University of California San Diego, US. Available at http://www.sccn.ucsd.edu/eeglab/) [18].

Statistical testing of evoked activity in the theta frequency band consisted of repeated-measures analyses of variance for power values over the time window that was determined by inspection of time–frequency plots (150–250 ms). A cluster of five electrodes was selected for statistical analyses on the basis of differential theta activity as revealed by the topographical difference plot (high-frequency minus low-frequency condition). Greenhouse–Geisser corrections were applied to adjust for violations of the sphericity assumption.

Low-resolution electromagnetic tomography (LORETA) was used to determine the underlying cortical generators of EEG activity in a narrow theta frequency band [19]. LORETA allows for the identification of the most plausible three-dimensional distribution of cortical current density, which accounts for a certain observed scalp EEG signal with an average localization error of approximately 10 mm [20].

For each participant, the EEG segments were averaged over all artifact-free trials per condition. In a first step, averaged 1000 ms epochs centering around the point in which theta power reaches peak values according to the time–frequency plots (−300 to 700 ms) were subjected to LORETA cross-spectral analysis for computation of the EEG activity in the frequency domain. The surface potentials at

27 electrode sites for the derived theta sub-band between 6 and 7 Hz (i.e. the center of theta activity as determined by S-transform) were then transformed into LORETA maps for each participant and condition.

To determine statistical significances of differences in regional neural activity between the experimental conditions, statistical nonparametric mapping procedures as implemented into the LORETA software package were used. Paired t-tests (two-tailed) comparing two of the three conditions were computed on a voxel-by-voxel basis over all participants. Voxels with t-values above the critical threshold ($P < 0.05$) were considered to represent regions of differential activation.

Results

As is evident from the plots derived by means of time–frequency analyses of the EEG data using S-transform, pronouns referring back to high-frequency nouns (Fig. 1c) elicit higher power in the theta range around 200 ms after their onsets than do pronouns that corefer to nouns with middle (Fig. 1b) or low lexical frequencies (Fig. 1a). Pronouns that are coreferential with low-frequency nouns yield the lowest values in evoked theta power in this time window.

Inspection of the topographical scalp distribution (Fig. 1d) of evoked theta band power (150–250 ms) identifies such a pattern of differential activity for a cluster of frontal electrodes with a slight shift to the right hemisphere (FZ/CZ/FC2/F4/C4).

This observation was confirmed by repeated-measures analyses of variance that revealed a significant effect of the antecedent noun's frequency during pronoun resolution in power in the theta frequency range (6–7 Hz) for this cluster of five electrodes between 150 and 250 ms [$F(2,46) = 5.29$, $P = 0.028$].

Subsequent LORETA analyses identified areas associated with differential theta activity (6–7 Hz) in the right medial temporal lobe (MTL). According to the LORETA solutions, the main source of activation was located in the para-hippocampal cortex (Fig. 2a). A second cluster in the left medial frontal lobe (subcallosal and medial frontal gyri) shows differences in theta band activity across experimental

Table I Sample stimuli for the three experimental conditions

Frequency	Exemplary stimuli
High	Rainer$_M$ hat ein Bild$_N$ [NP/O] seiner Freundin$_F$ in der Brieftasche$_F$. Er$_M$ schaut **es$_N$** [PRO/O/N] gerne an. (Rainer carries a picture of his girlfriend in his wallet. He likes to look at it).
Middle	Maria$_F$ hat ein Foto$_N$ [NP/O] ihrer Tochter$_F$ auf dem Schreibtisch$_M$. Sie$_F$ schaut **es$_N$** [PRO/O] häufig an. (Maria has a picture of her daughter on her desk. She often looks at it).
Low	Iris$_F$ hat ein Porträt$_N$ [NP/O] ihres Vaters$_M$ über der Couch$_F$. Sie$_F$ schaut **es$_N$** [PRO/O] täglich an. (Iris has a portrait of her father above the couch. She looks at it every day).

NP, noun phrase; PRO, pronoun; OBJ, object; F, feminine; M, masculine; N, neuter.
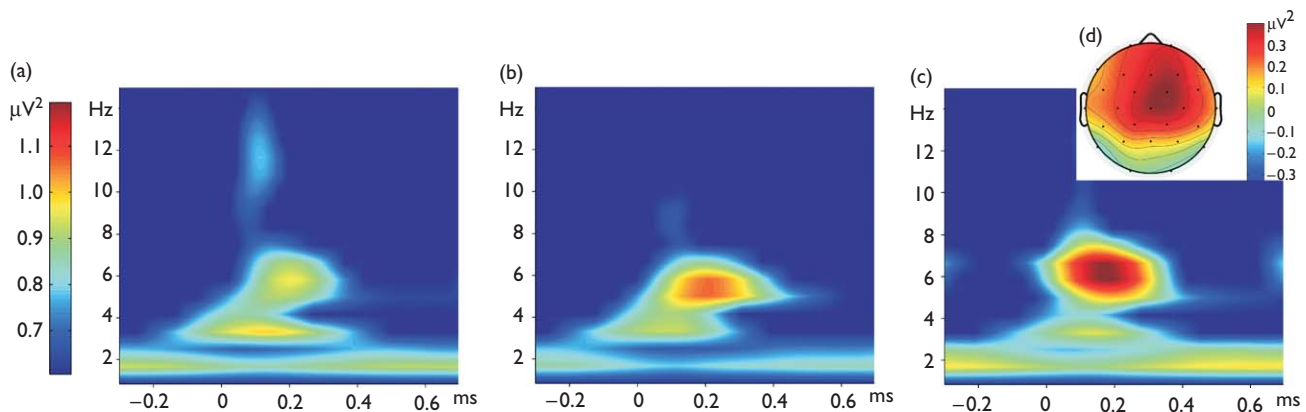The onsets of elecroencephalograph measures are highlighted in bold face.

Fig. 1 Time–frequency plots for the critical time window around pronoun onset revealing patterns of evoked activity (averaged power values in μV^2, n=24) for pronouns referring back to (a) low frequency, (b) middle frequency, and (c) high-frequency nouns at electrode site FZ in the frequency range between 0.1 and 15 Hz, and (d) topographical difference plot (high-frequency minus low-frequency condition) showing differences in evoked power (μV^2) in the upper theta band (6–7 Hz) for the time window between 150 and 250 ms after pronoun onset.
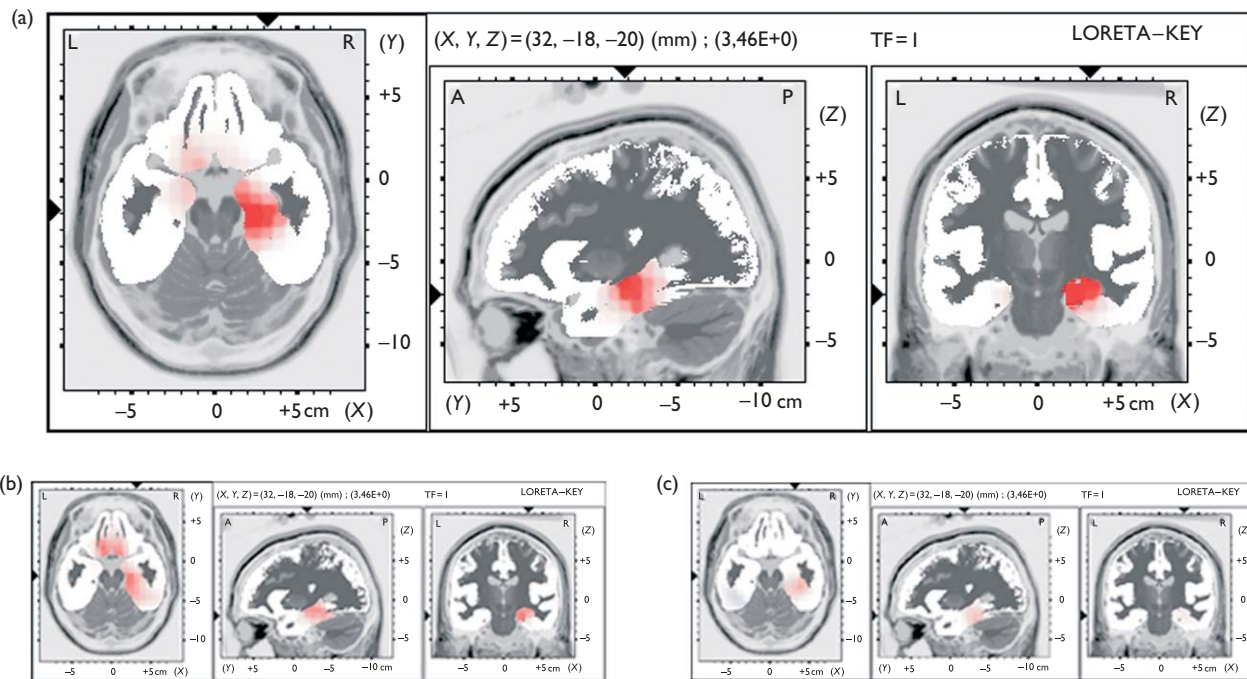
Fig. 2 Results of the low-resolution electromagnetic tomography (LORETA) *t*-statistics comparing evoked activity in the theta band (6–7 Hz) time locked to the presentation of coreferential pronouns for the experimental conditions: (a) high minus low-frequency condition, (b) middle minus low-frequency condition, and (c) high minus middle frequency condition. All images are scaled to a common maximum *t*-value to allow direct comparisons between conditions. The images show LORETA slices in Talairach space (*x*=32, *y*=−18, *z*=−20) for the estimated source distributions of activation differences.

conditions too, albeit to a lesser degree. Comparing the two extreme conditions, that is, pronouns referring to high-frequency versus pronouns referring to low-frequency nouns, LORETA nonparametric statistical analyses revealed significant effects for differential activity in the theta band in the right medial-temporal region ($x=18$, $y=−18$, $z=−20$; $t=3.60$, $P=0.036$, two-tailed). Although similar patterns of maximal differences in current source density for the theta range are discernible from the LORETA images for both comparisons between the high versus middle frequency (Fig. 2c) and the middle versus low-frequency conditions (Fig. 2b), statistical nonparametric mapping tests yielded no significant results.

Discussion

To clarify the issue of whether advantages in the resolution of pronouns referring back to low-frequency nouns reported by van Gompel and Majid [1] are related to memory processes, as the amplitude differences of the P300 component found by Heine *et al.* [5] suggest, activity in the theta band of the EEG was submitted to detailed analyses in the present study. For the time window between 150 and 250 ms, evoked theta power in a right-frontal cluster of electrodes was shown to differ significantly between the three experimental conditions, with highest power values evoked by pronouns referring to high-frequency nouns and smallest activation for the low-frequency conditions. Similar patterns of changes in theta power concomitant with P300 amplitude effects were described before [11].

The interpretation of differential theta activation is straightforward, as brain responses in the theta frequency

band of the human EEG have been shown to be involved in memory performance with respect to load on working memory resources. The so-called frontal midline theta has been shown to increase in power with higher load on working memory resources in the context of classical working memory tasks such as n-back [21] or Sternberg paradigms [22].

Our results are well in line with the so-called elevated attention hypothesis, which proposes that allocation of attentional resources during encoding of low-frequency words facilitates subsequent processes of retrieval from short-term memory [23]. In any sentence context, low-frequency nouns are highly salient entities that attract more attention than nouns occurring more frequently in natural language. Attention-related differences in encoding processes for different frequency classes of nouns mediate the resolution of coreferential pronouns occurring later in a given text.

Our finding that the main source of theta activation can be traced to the right MTL is of special interest. The MTL, a cortical system consisting of the hippocampal region and the adjacent perirhinal, entorhinal, and parahippocampal cortices, is assumed to be part of a higher order association network that mediates memory processes by contributing to stimulus maintenance over periods of delay and to stimulus-matching functions [24].

The parahippocampal region (PR), which was shown to be the main source of theta activation according to the LORETA analyses, is assumed to serve as a buffer mechanism for the representation of specific items [25]. In the context of the hippocampal–parahippocampal interplay, the role of the PR is to maintain the representations of

particular items active during memory delays, whereas the hippocampus engages in the processing of relational content of stimulus events. Taking into account the comparably low spatial resolution of LORETA, however, the activation of such an association network during pronominal resolution appears to be plausible, as pronouns typically serve as indexes for specific items in a given linguistic context and receive their full meaning only if the relationships in a complex semantic environment are processed correctly.

Conclusion

Processing advantages for pronouns referring back to nouns with low lexical frequencies over pronouns that corefer with high-frequency nouns are reflected in differential activations in the theta band of the EEG. Elevated attention during encoding of low-frequency nouns mediates subsequent retrieval at the point where a pronoun occurs in a sentence. Activation of the PR implicates the workings of an intermediate-term store for specific items in the context of pronominal resolution.

Acknowledgement

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