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Investigating the influence of proficiency on semantic processing in bilinguals: An ERP and ERD/S analysis

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In this study, we presented sentences either ending with high or low probability cloze words or semantically incongruent words to investigate the influence of L2 proficiency on electrophysiological correlates of semantic processing in bilinguals. Event-related potentials (ERPs) as well as the oscillatory dynamics of the EEG signal, specifically, frequency power changes expressed as event-related (de)synchronization (ERD/S), were analyzed. Replicating earlier results, we found an N400 on semantically incongruent words, as well as on low cloze probability words. For the bilinguals investigated in the present study, N400 latency in the low cloze probability condition was found to be modulated by L2 proficiency, indicating that L2 proficiency in our sample might have influenced the speed of semantic integration. Relative Theta power increased for all three word conditions, but no influence of proficiency was observed. Different from the ERP results, we found a stronger increase in theta power for low cloze probability words than for incongruent and high cloze probability words, especially over temporo-parietal brain areas. The spatial distribution of the theta ERD/S results also differed from the N400 topography. Whereas the N400 showed a typical topography with a maximum over temporo-posterior electrode positions, the theta ERD/S topography was maximal for high and low cloze probability words over left central-posterior electrode positions. These findings show that the ERP and ERD/S results are sensitive to semantic processing. The different pattern of the ERD/S results compared to the ERP results, functionally and with regard to topography, suggests that the ERD/S reflects a different aspect or stage of semantic processing, possibly the successful conceptualization of a sentence.

Key words: cloze probability, sentence processing, bilingual, EEG oscillation, theta, N400

INTRODUCTION

To date, electrophysiological studies of language processing have mainly focused on the analysis of event-related potentials, or ERPs. For example, the N400 ERP component has been associated with the processing and integration of word meaning (Kutas and Hillyard 1980). Recently, however, time-frequency analyses have been employed in psycholinguistic research with the aim to gain additional insight into semantic processing beyond the information represented by ERPs (e.g., Bastiaansen et al. 2005, 2008, 2010, Hald et al. 2006). In the present study, we investigated the processing of sentences in bilinguals using ERPs as well as time-frequency analyses.

The N400 component is a negative-going wave approximately 400 ms after stimulus presentation. It has first been observed when the reading of semantically inappropriate words in a sentence was compared to semantically appropriate words (Kutas and Hillyard 1980, 1983). For example, an N400 was observed, when a sentence like 'He spread the warm bread with ...' finished with the semantically inappropriate word 'socks' but not when a sentence finished with a semantically plausible (e.g. 'butter') or a syntactically wrong word. The N400 has therefore been interpreted to be specifically related to semantic processing (Kutas and Hillyard 1983). More specifically, the N400 has been interpreted as an index of 'contextual integration,' reflecting the goodness of fit between a word and its context (Hagoort

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and Brown 1995). It has been observed, for example, that semantically incongruent words elicit a larger N400 at the end of a sentence when a semantic context has been established rather than at the beginning of a sentence (van Berkum et al. 1999). The N400 is viewed as a first indicator for semantic memory processes. It should be noted however, that the N400 has not only semantic properties but also reflects processes of lexical access. It has been observed, for example, that the N400 is modulated by different psycholinguistic properties of words, such as, for example, word frequency (Kutas and Federmeier 2000) or orthographic neighborhood size (Holcomb et al. 2002). Lexical access is a processing stage that takes place earlier, namely, about 200 ms after stimulus-onset (Penolazzi et al. 2007). It has therefore been proposed that the N400 could be separated from an earlier component, the N350, that reflects lexical processing (Pylkkänen and Marantz 2003, for a review, see Pulvermüller et al. 2009), whereas the N400 proper is rather assumed to be related to processes after lexical access. These processes include re-processing and integrating context-related information (Penolazzi et al. 2007) as well as semantic or verbal memory use during language comprehension (Salisbury 2004).

Importantly for the aim of the present study, the N400 has been shown to be sensitive to the semantic relationship of words within a sentence. Words that are less expected (low cloze probability words) than others (high cloze probability words) in a sentence context elicit a larger N400 amplitude (for a review, see Kutas and Federmeier 2000). For example, a sentence like 'He turned on the radio and listened to the' is expected to finish on 'music' (high cloze probability) rather than 'commentary' (low cloze probability). It should be noted that the N400 as a component often has negative amplitude values when compared to baseline. However, as in the present paper, the N400 is often reported in comparison to another condition, such as sentences with high closure probability.

The overall robustness of the N400 makes it a useful tool in bilingualism research to investigate the automaticity of semantic processing in second language learners (Ardal et al. 1990, Hahne and Friederici 2001, Proverbio et al. 2004, for a review, see Mueller 2005). Typically, semantic violation paradigms are used (Moreno et al. 2008). Bilinguals were observed to show a reduced N400 in their first learned foreign language (L2) compared to their native language (L1). Late bilinguals, that is, when they were exposed to their L2 language after age eleven, have also been observed to show a later peak of the N400 (Weber-Fox and Neville 1996), which has been interpreted to reflect an extended lexical search and a lower degree of automaticity of L2 processing compared to L1 (Ardal et al. 1990). A modulation of the N400 amplitude by L2 proficiency, however, has not been consistently observed (e.g. Ardal et al. 1990). While the N400 has been extensively studied as an index for semantic processing, other properties contained in the EEG signal, such as its frequency composition and other aspects of its oscillatory dynamics, have received comparatively less attention from researchers in psycholinguistics. One possibility to investigate the oscillatory dynamics of the EEG signal is to track changes in specified frequency spectra over time. An increase in power for a designated frequency band is usually referred to as event-related synchronization (ERS), whereas a decrease in power is referred to as event-related desynchronization (ERD) (Pfurtscheller and Lopes Da Silva 1999). An analysis of ERD/S yields different information than an ERP analysis. Since ERPs are calculated by averaging the EEG signal over epochs locked to the onset of stimulus presentation for a specific condition, ERPs represent only electrical activity that is time- and phase-locked to the stimulus. In contrast, an ERD/S analysis yields signal information that is not phase-locked with the stimulus presentation. It should be noted, that, without additional corrections, non-phase locked EEG activity includes phase-locked components that cannot be distinguished when both are in the same frequency band range. One technique to overcome this problem is to use calculate band power changes using the intertrial variance of bandpass filtered EEG data (Kalcher and Pfurtscheller 1995). Then an ERD/S analysis is conducted for a specific frequency band. Typically, in an ERD/S analysis, absolute band power is transformed into relative power changes for an activation epoch relative to a baseline interval (Lopes Da Silva 2006).

In language processing, different types of information that are distributed over different brain areas have to be integrated. This binding might be brought about by the synchronization of oscillatory neural activity (Hald et al. 2006). Modulations in neuronal synchronization, particularly changes in theta band power, have been especially been related to memory processes. Theta oscillations have been interpreted as reflecting resonating hippocampal-neocortical loops, driven primarily by the hippocampus or, possibly, also by neocortical regions (Buzsáki 2006, p. 336). In recollection, theta oscillations are assumed to play a role in coordinating the retrieval of different types of information distributed over the neocortex (Düzel et al. 2010). Another possible role of oscillatory synchronization in memory is as a principal mechanism of learning *via* spike timing-dependent plasticity (Caporale and Dan 2008, Jutras and Buffalo 2010). Band power increases in the theta frequency range (3–8 Hz) have been associated with a faster learning rate in animals (Nokia et al. 2008) and greater retrieval success in humans (Klimesch et al. 2001).

The oscillatory dynamics of the EEG signal has also been shown to be sensitive to semantic processing during language comprehension (for a review, see Bastiaansen and Hagoort 2006). Bastiaansen and colleagues (2005) observed that semantically rich materials, such as open class words (nouns, verbs), elicited a stronger increase in theta band power than semantically poor materials, such as closed class words (grammatical elements). The theta power increase also showed a left temporal distribution. Furthermore, Bastiaansen and coauthors (2008) also observed a selective sensitivity of theta topography to the semantic properties of words. This led the authors to associate theta power specifically with lexical-semantic retrieval processes. Bastiaansen and colleagues (2010) also observed a stronger increase in theta band power for sentences with a correct syntactic structure as opposed to sentences with a wrong syntactic structure and random word sequences: The authors related these results to development of a mental representation of the sentence meaning and the gradual formation of a working memory trace of the sentence. It should be noted, however, that a different pattern of results was observed by Hald and coworkers (2006), where an increase in theta band power has been observed for semantic violations within a sentence context. Although, so far, not many studies have evaluated semantic processing with theta power, it can be concluded that theta power is sensitive to semantic processing. Furthermore, the evidence so far also shows that the results of N400 and theta power differ functionally and have a different topography (Bastiaansen et al. 2008). This indicates that both measures reflect different aspects of semantic processing. Time-frequency analyses might add useful and complementary information to ERP results about the influence of proficiency on semantic processing in bilinguals. It could be speculated that, while the N400 represents the difficulty of contextual integration, theta oscillations might reflect successful conceptualization. Successful conceptualization implies the build up of a meaningful idea that can be stored as one unit in memory. This fits very well with the notion that theta oscillations are related to memory functions in encoding and retrieval (Bastiaansen and Hagoort 2006).

In the present experiment, semantic processing in bilinguals was investigated during reading. Short incomplete sentences were presented that would end either in a high probability cloze word, a low probability cloze word or a semantically incongruent word. The participants had to judge the acceptability of the complete statement. They had to indicate by key press whether a sentence was semantically plausible (high and low cloze probability word) or implausible (semantically incongruent word). We designed our study to be comparable to the study by Proverbio and others (2004), who observed an N400 on incongruent words in L2. To investigate the N400 also for plausible but unexpected sentence endings we expanded the design of the study by Proverbio and colleagues (2004) by adding a condition (low probability cloze words). We also intended to look beyond ERPs by investigating the oscillatory dynamics of the EEG signal. We focus specifically on theta band power because this frequency band has been associated with memory retrieval processes (Klimesch et al. 2001), the formation of an episodic memory trace of (Bastiaansen et al. 2002), and semantic processes (Hagoort et al. 2004, Bastiaansen et al. 2005, 2008, 2010, Hald et al. 2006). With regard to ERPs, we hypothesized that semantically incongruent words should yield a larger N400 than high cloze probability words. Low cloze probability words are also expected to give rise to an N400 compared to high cloze probability words but with lower amplitude than semantically incongruent words. This has been observed in previous studies for native speakers (Kutas and Federmeier 2000) as well as for bilinguals (Moreno and Kutas 2005). With regard to the frequency analysis, it is not clear, what to expect. On the basis of the study by Hald and coworkers (2006) a lower rise in theta power could be expected for meaningful sentence endings (high and low cloze probability) as compared to sentences ending in semantically incongruent words. Based on the results by Bastiaansen and others

(2005, 2008, 2010), however, a stronger rise in theta power could be expected for meaningful sentence endings (low and high cloze probability words) as compared to meaningless sentences ending in semantically incongruent words.

With regard to L2 proficiency, we hypothesized a negative correlation between L2 proficiency and the latency of the N400, as observed previously (Ardal et al. 1990, Kutas and Kluender 1991, Moreno and Kutas 2005). On the one hand, late bilinguals, especially those with lower proficiency levels, might take longer than native speakers simply to access words in the mental lexicon. This might lead to semantic integration to be delayed and result in a later latency of the N400. If the N400 is related to word level processes (speed of lexical access) a negative correlation between proficiency level and peak latency of the N400 should be observed in all conditions. If, on the other hand, the delay of the N400 reflects a delay on the level of semantic or conceptual integration rather than word level processes, such a correlation should only be observed for words finishing conceptually plausible sentences. With regard to the influence of L2 proficiency on theta amplitude, we would expect that L2 speakers with a lower proficiency take longer to generate a mental representation of the sentence. Following Bastiaansen and coauthors (2008) the increase in theta amplitudes for sentence-like materials compared to random word sequences reflect increased demands on working memory during the generation of a mental representation of the sentence. If L2 speakers with lower proficiency take longer to generate such a mental representation, this delay might incur higher working memory demands that translate into a negative correlation with theta amplitude.

METHODS

Participants

Twenty-two female healthy young adults took part in this study. All participants were native speakers of German, right-handed and had normal or corrected-to-normal vision. They were paid for their participation and gave written informed consent. Due to technical problems, two students had to be excluded from the analysis, leaving twenty participants with a mean age of 24.2 years (SD 2.7). All participants were proficient speakers of English; they were advanced students at the faculty of translation and interpreting (English–German) at the University of Graz. All participants had a mean exposure time to L2 of 8.47 years (SD 1.68) and had learned the language at an average age of 14 years (SD 2.96). To assess their second language proficiency in English, they were screened with the computer-based English proficiency test DIALANG (Huhta et al. 2002). The mean proficiency level of all participants in this test was within the second highest proficiency level (mean score = 798 out of a possible maximum of 1 000, SD 153).

Materials

50 simple English sentences were constructed with the final word having either a high or low cloze probability, or being semantically incongruent. For example, a sentence beginning with 'The surgeon tried in vain to save his ...' would end either with the final word 'patient' (high cloze probability), 'son' (low cloze probability) or 'answer' (semantically incongruent). The sentence stems, as well as low and high cloze probability final words were taken from Bloom and Fischler (1980). Bloom and Fischler assessed cloze probability for their materials with a sample of 100 participants. According to Bloom and Fischler (1980), the high probability clozes had a mean completion probability of 0.73 (SD 0.15) whereas the low probability cloze words had a mean completion probability of 0.05 (SD 0.04). For the present study an additional set of semantically incongruent final words was constructed (see supplementary data for a full listing of materials). These words were matched with the high and low probability cloze words from Bloom and Fischler (1980) with regard to their frequency of occurrence (log-transformed Hyperspace Analogue to Language (HAL) frequency norms; Lund and Burgess 1996, Balota et al. 2007). The mean frequency values for the three word types were 10 222 (SD 1 323) for the high cloze probability words, 10 217 (SD 1 286) for the low cloze probability words, and 9 735 (SD 1 493) for the semantically incongruent words. Word frequency did not differ significantly between the three word types ($F_{2,98}$=1.935, P=0.15). The mean word length values for the three word types were 4.74 letters (SD 1.10) for the high cloze probability words, 4.90 (SD 1.37) for the low cloze probability words, and 4.88 (SD

1.51) for the semantically incongruent words. Word frequency did not differ significantly between the three word types ($F_{2,98}$=0.221, P=0.80). The materials were also analyzed with regard to differences in concreteness and imageability ratings (MRC Psycholinguistic Database by Coltheart 1981*)*. No significant differences were observed between conditions, either for concreteness ($F_{2,90}$=0.29, P=0.75; high cloze: M 524.7, SD 86.22; low: M 511.22, SD 92.6; incongruent: M 510.54, SD 113.03) or for imageability ($F_{2,90}$=0.49, P=0.61; high cloze: M 544.35, SD 71.19; low: M 529.35, SD 68.96; incongruent: M 539.89, SD 82.62). Each of the 50 sentence stems was used three times, each time ending with a different final word from one of the three cloze conditions (high, low, incongruent). In total, 150 sentences were presented.

Apparatus and procedure

Participants were seated in a dimly lit, acoustically and electrically shielded booth in front of a high-resolution PC monitor with a viewing distance of approximately 100 cm. The sentences and the cloze word were presented in white letters with a font size of 72 pt in Arial on a black background. Participants responded using the computer keyboard. Stimulus presentation, triggering, and response recording were controlled by the program Translog 2006 (Jakobsen and Schou 1999).

Every trial started with the presentation of a fixation cross for 3 000 ms (see Fig. 1A for a trial timing schema). It was replaced by the sentence stem, which remained on the screen for 2 500 ms. Then a fixation cross was shown for 1 500 ms, and replaced by the final word of the sentence. The sentences and the cloze word were presented in white letters with a font size of 72 pt in Arial on a black background. Responses were recorded from the onset of the presentation of the final word. Participants had 3 000 ms to answer after the onset of the presentation of the sentence final word. The presentation of the final word was response-terminated and replaced by a fixation cross. The following trial started 3 000 ms after the response. The pause before the sentence final word was inserted for two reasons. First, this procedure ensured that the all participants, especially those with a medium proficiency level in L2 had fully understood the sentence upon encountering the critical sentence final word. Only this measure ensures that a correlation between the L2 proficiency level and EEG correlates can be interpreted as being due to a difference with regard to the successful integration of the sentence final word into the conceptual representation of the sentence, rather than to a greater rate of comprehension failure in the participants with lower proficiency levels. If we had presented the sentence final word immediately after the sentence stem, participants with medium proficiency levels might be forced to abort semantic and conceptual integration, because they cannot integrate the meaning of a sentence in limited time. A second reason for our choice was to have a paradigm that is comparable to the one used by Proverbio and coworkers (2004), who also tested L2 participants.

Participants were instructed to read the sentences and, on presentation of the sentence final word, to judge whether the sentence would make sense, that is, whether it is semantically acceptable or plausible. To give an 'acceptable/plausible' answer on sentences with high or low cloze probability endings, participants were instructed to use their left and right index fingers to simultaneously press the keys for number 7 and 9, respectively, on the numeric key pad of the computer keyboard. To give an 'not acceptable/implausible' answer on sentences with a semantically incongruent ending, they were instructed to simultaneously press the number keys 1 and 3 on the numeric key pad, with their left and right thumb, respectively. A bimanual response was chosen to avoid unilateral motor artifacts in the EEG signal. Participants were also instructed to minimize their eye movements and to avoid eye blinks during the time of the presentation of the sentence final word.

Before the start of the main experiment, participants were presented with ten sample sentences for practice. The sentence materials for practice were separately constructed and not taken from the stimulus materials described above. The 150 stimulus sentences were presented in three blocks, each consisting of 50 pseudo-randomized trials. A single block lasted approximately ten minutes, depending partly on the individual response times of each participant. Between blocks, participants were allowed a short break. After the EEG measurement, the participants completed the DIALANG test to assess individual proficiency in English.

EEG recordings and data analysis

Scalp potentials were collected using a cap with 58 active electrodes (Acticap, BrainProducts GmbH, Munich, Germany) based on the extended 10–20 system (see Fig. 1B). All electrodes were referenced to the nose. For EEG recording, a BrainAmp amplifier (BrainProducts GmbH, Munich, Germany) was used. Vertical and horizontal EOG was recorded with three electrodes in total, two were placed on the outer canthi of the eyes and one was placed superior to the nasion. EEG and EOG signals were digitized with a sampling rate of 500 Hz and prefiltered with a 0.1 Hz high-pass and a 100 Hz low-pass filter. Electrode impedances were kept below 5 kΩ for the EEG recording and below 10 kΩ for the EOG recording.

Data preprocessing and analysis was performed with the Brain Vision Analyzer software package (version 1.02, BrainProducts GmbH, Munich, Germany). The EEG data was filtered using a 0.5 Hz to 70 Hz bandpass phase shift-free Butterworth filter with a slope of 48 dB/oct and a 50 Hz notch filter. Ocular artifacts (eye blinks and eye movements) were automatically corrected using the algorithm developed by Gratton and colleagues (1983). This algorithm is based on linear regression. It first uses EOG and EEG

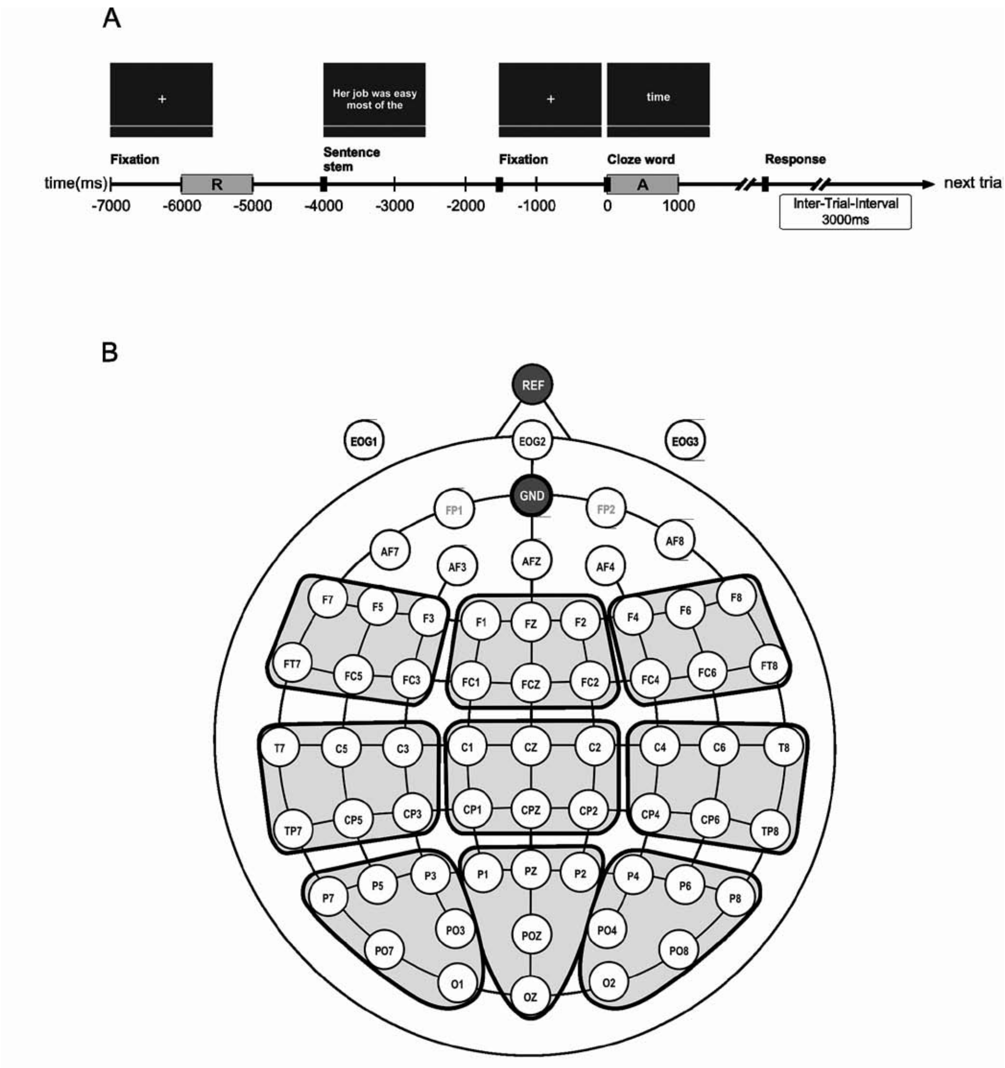

Fig. 1. Trial timing scheme and topography of recorded EEG electrode positions. (A) Trial timing schema. All analyses (RT, ERP, ERD/S) were time-locked to the onset of the sentence final word. The grey rectangle A denotes the activation period, the grey rectangle B shows the reference interval for the time-frequency (ERD/S) analysis. (B) Topography of recorded EEG electrode positions. The electrode positions pertaining to the regions selected for the statistical analysis are indicated with black rectangles.

recordings to calculate propagation factors for eye blinks and eye movements that are assumed to reflect the influence of eye artifacts on the EEG traces. The propagation factors typically have a centro-frontal distribution and are larger for saccades than blinks. Additional correction factors are computed on data at each time point on every trial after event-related activity has been subtracted (Gratton et al. 1983).

After ocular artifact correction, automated rejection of other EEG artifacts was performed for the critical time window from the fixation cross at the beginning of each trial to 1 000 ms after the onset of the sentence final word onset (Criteria for rejection: >70.00 μV voltage step per sampling point, >300.00 μV and <0.10 μV voltage difference between two time points within the critical time window, absolute voltage value >±200.00 μV). After artifact correction the data was downsampled to 250 Hz. For the ERP and the time-frequency analysis (ERD/S) different time windows were considered as critical. The critical time windows for the ERP analysis were: −100 to 1 000 ms (activation interval), −100 to 0 ms (reference interval) and for the time-frequency analysis: 0 to 1 000 ms (activation interval), −6 000 to −5 000 ms (reference interval), with 0 ms denoting the onset of the presentation of the sentence final word. All critical time windows (epochs) with artifacts were excluded from the ERP analysis and the time-frequency analysis (6.2% of all trials). As the overall error rate in the rating task was low (6.9% in total, see below), both analyses were performed on all trials.

ERP-analysis

For each participant, averaged ERP waveforms were computed across trials separately for each cloze condition (see Fig. 3). The 100 ms interval before the presentation of the final word (−100 ms to 0 ms) was used as baseline interval. For statistical analysis, a time window from 330 to 560 ms after the onset of the sentence final word onset was selected for the N400. Within this time interval, the average of the amplitude values as well as the latency to peak was determined. For statistical analyses, nine topographical areas or regions of interest were defined (see Fig. 1B) and the signal of the single electrodes within each region was averaged. The electrode positions within the regions were: left anterior: F3, F5, F7, FC3, FC5, FT7; left central: C3, C5, T7, CP3, CP5, TP7; left posterior: P3, P5, P7, PO3, PO7, O1; mid-anterior: F1, Fz, F2,FC1, FCz, FC2; mid-central: C1, Cz, C2, CP1, CPz, CP2; mid- posterior: P1, Pz, P2, POz, Oz; right anterior: F4, F6, F8, FC4, FC6, FT8; right central: C4, C6, T8, CP4, CP6, TP8; right posterior: P4, P6, P8, PO4, PO8, O2.

In language comprehension, Broca's area within the left frontal cortex and Wernicke's area in the left temporo-parietal cortex are predominantly involved. Although surface potentials do not directly allow inferences about the underlying signal sources, differences with regard to surface potential topography could be expected between frontal, central and posterior electrode positions, as well as with regard to laterality (left, center, right) and should be investigated. In this choice of regions we followed other studies of the N400 in language processing (Hahne and Friederici 2001, Elston-Güttler et al. 2005). The averaged voltage values (averaged over all electrodes of a region) per participant and condition were entered into a repeated measures ANOVA with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior) and HEMISPHERE (left, center, right). To explore significant effects, Bonferroni *post-hoc* comparisons between experimental conditions were calculated. For the analysis of variance, degrees of freedom were Greenhouse-Geisser corrected for violations of the sphericity assumption; the probability of a Type I error was maintained at 0.05. Below, we report *P*-values corrected for sphericity. For greater clarity, uncorrected degrees of freedom are reported. For visualization purposes (N400 topography), the mean amplitudes values within the N400 time window (330 to 560 ms) for each electrode site were color-coded and interpolated between electrode sites. To investigate the influence of the level of L2 proficiency on the results, correlations were calculated between the individual DIALANG scores with values of the N400 component (averaged amplitude and latency) per condition. The correlations were calculated over the averaged values for the defined regions.

Time-frequency (ERD/S) analysis for different frequency bands

The temporal dynamics of the EEG signal was investigated based on time-frequency analyses of the EEG signal to yield event-related desynchronization/synchronization (ERD/ERS or, short, ERD/S) (Pfurtscheller and Lopes Da Silva 1999). In the present article, we will use the ERD/S terminology to describe power changes in specific frequency bands. For a specified frequency band, ERS indicates a power increase and ERD indicates a power decrease, relative to a reference interval. First, the evoked components within the EEG signal were removed to leave only the induced activity within the EEG signal (Kalcher and Pfurtscheller 1995). To achieve this, the event-related activity was first calculated by averaging all trials in the time windows from −7 000 ms to +2 000 ms for each condition and participant. This averaged activity was then subtracted from the EEG signal. The frequency composition and ERD/S of the remaining signal was analyzed as follows: first, the preprocessed continuous EEG signals were bandpass-filtered to extract 2 Hz frequency bands between 2 Hz and 40 Hz, overlapping by 1 Hz, resulting in 39 different frequency bands. For the calculation of the power within the specific frequency bands, the amplitude values of the filtered samples were squared and smoothed with a moving average filter of varying length (Graimann et al. 2002). The continuous power values *A(t)* at time *t* were then normalized to the reference interval (from −6 000 ms to −5 000 ms) according to the following equation:

$$\mathrm{ERD/S}(t) = \left(\frac{A(t)}{R} - 1\right) \bullet 100\%$$

ERD/S values were calculated for all frequency bands for each participant, experimental condition (high, low, incongruent), and electrode site. A method to summarize and visualize the results of the ERD/S analysis for all frequency bands are ERD/S maps (time-frequency maps). To visualize the frequency bands that show a power increase or decrease modulated by the different conditions, an ERD/S map was calculated. In this map, the power change within a specific frequency band is given by a color code, with time represented on the x-axis and frequency band on the y-axis (see Fig. 2). Differences were only visible within the theta frequency band (4–7 Hz).

Time-frequency (ERD/S) analysis for the theta band

Although an ERD/S map has only illustrative value, the further analysis is focused on the theta frequency band, for theoretical considerations. Previous research has indicated that power changes in the theta band can be associated with memory encoding and retrieval, as well as with semantic processing (e.g., Hald et al. 2006). The theta ERD/S time courses showed a peak within a time window between 300 and 600 ms after the onset of the sentence final word. For statistical analysis, the mean ERD/S values in this time window were averaged per participant and entered into a repeated measures ANOVA with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior) and HEMISPHERE (left, center, right), similar to the statistical analysis of the N400. To ensure that differences observed in the activation period after the onset of the sentence final word are not due to bandpower differences in the reference interval, an additional statistical analysis was conducted on the reference interval bandpower (−6 000 to −5 000 ms). For this analysis, logarithmic bandpower values in the reference time window were averaged to get normally distributed data, per participant and condition. These values were then entered into a repeated measures ANOVA with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior), HEMISPHERE (left, cen-

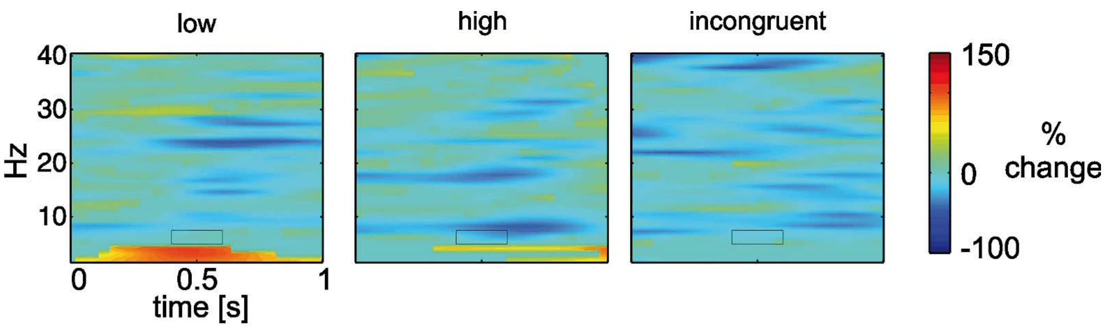

Fig. 2. Time-frequency representations of one participant for the electrode at Fz, separately for the three cloze conditions: high probability, low probability and incongruent. Red indicates an event-related bandpower increase (ERS), whereas blue indicates a decrease (ERD). The black rectangles indicate the theta frequency band (4–7 Hz) in the time window from 300 to 600 ms after the onset of the sentence final word.

ter, right). To generate a topography of the relative increase in theta power within the specified interval (300 to 600 ms) over all electrode positions, average ERD/S values for each condition were color coded and interpolated between electrode positions. To exclude that the observed differences between conditions were due to a difference already present in the reference interval, an additional statistical analysis was conducted for the reference period from −6 000 to −5 000 ms before the onset of the sentence final word. No significant differences were observed.

RESULTS

Behavioral data

The overall error rate was 6.9 percent. Most errors were observed for sentences with low probability clozes (16%, SE 1.95), followed by sentences with high probability clozes (2.2%, SE 0.54) and incongruent clozes (2.5%, SE 0.56). Error rates were $2\arcsin\sqrt{p}$ transformed to achieve approximate variance equality (Bishop et al. 1975, p. 367 ff). The transformed error rates were then entered into a repeated measures ANOVA with the factor CLOZE (high, low, incongruent). The differences in error rates for the three different conditions is reflected by a significant main effect of the factor CLOZE ($F_{2,38}$=41.74, MSE=0.05, P<0.001). It should be noted, that it is unlikely that the high error rate in the low probability condition is due to insufficient L2 proficiency of our participants with regard to lexical knowledge. In all three conditions, our stimulus materials were controlled for word frequency as well as other variables that influence lexical access. Therefore, a high error rate should have been observed in all three conditions.

For the analysis of the reaction times, only correctly answered trials were taken into account. In addition, outliers which were under 150 ms or above 3 000 ms were discarded (total: 18 trials, 0.6%). The reaction times for the correctly answered trials were entered into a repeated measures ANOVA with the factor CLOZE (high, low, incongruent). Reaction times were longer for low probability clozes (1.47 s, SE 0.08 s) than for semantically incongruent final words (1.18 s, SE 0.06 s) and fastest with sentences ending with a high probability cloze (1.04 s, SE 0.05 s), [$F_{2,38}$=50.02, MSE=0.02, P<0.001].

To investigate a possible modulation of L2 proficiency on the behavioral results, correlations were calculated for the participants DIALANG scores with the reactions times and the transformed error rates in every condition. No significant correlations were observed.

ERP analysis – N400

For all three conditions, a negative-going deflection in the ERP component was observed after the onset of the sentence final word. With a mean peak latency between 411 ms for low cloze probability sentences to 424 ms for high close probability sentences this component can be interpreted as an N400. Grand-average ERPs and scalp topographies for all three conditions are given in Figure 3A and B.

N400 amplitude values against baseline were entered into a repeated measures ANOVA with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior) and HEMISPHERE (left, center, right). The N400 amplitude was largest for sentences with incongruent words (−4.09 µV, SE 0.53 µV) than for sentences with low cloze probability words (−1.82 µV, SE 0.54 µV) and high cloze probability words (0 µV, SE 0.51 µV), which is reflected in a significant main effect of CLOZE ($F_{2,38}$=36.56, MSE=757.23, P<0.001). N400 amplitudes also differed between anterior, central or posterior sites, depending on condition, which gave rise to a significant interaction CLOZE × REGION ($F_{4,76}$=20.41, MSE=26.11, P<0.001). For incongruent clozes larger amplitudes were found within central (−4.54 µV, SE 0.61) and parietal regions (−4.77 µV, SE 0.69; P<0.05, Bonferroni *post-hoc* test) than anterior regions (−2.97 µV, SE 0.39). For low cloze probability words a larger N400 amplitude was found in central regions (−2.16 µV, SE 0.58) compared to anterior regions (−1.37 µV, SE 0.45). The opposite pattern was found for high cloze probability words: A tendency was found for a larger N400 amplitude within the posterior region (0.54 µV, SE 0.59) than in the anterior region (−0.27 µV, SE 0.45). Furthermore, hemisphere differences were found for the incongruent words: In the anterior region a larger N400 was observed in the right hemisphere (−3.80 µV, SE 0.38 µV) compared to the center region (−2.75 µV, SE 0.47 µV) and the left hemisphere (−2.34 µV, SE 0.47 µV). In central and posterior regions N400 amplitudes were larger in the right hemisphere (central:

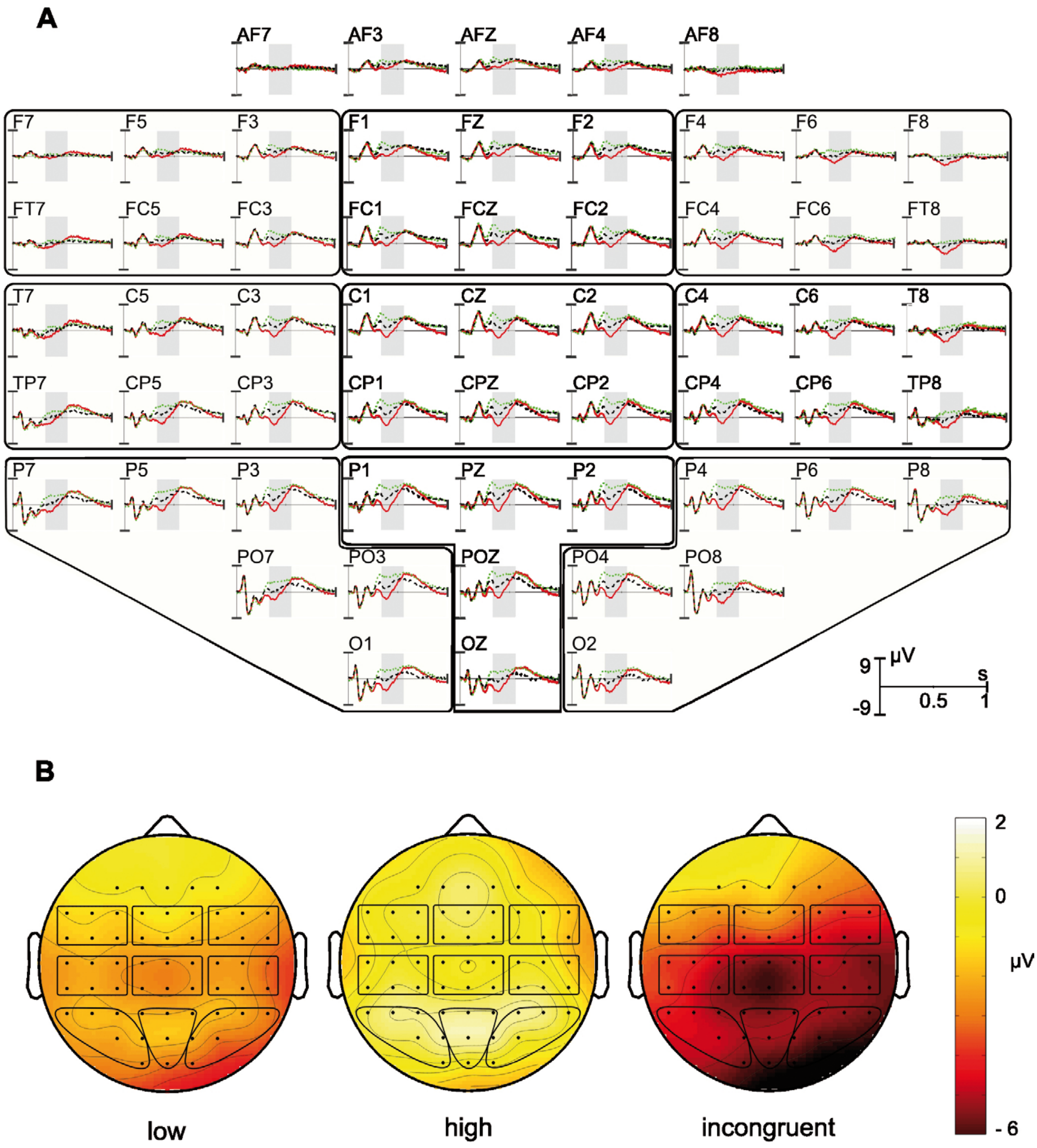

Fig. 3. ERP time course and scalp topographies of the N400. (A) ERP time course at selected electrode sites for the incongruent clozes (red solid line), the low probability clozes (black dashed line) and the high probability clozes (green dotted line). The time window of the N400 component (330 to 560 ms) is indicated in gray. (B) Scalp topographies of the N400 for the three conditions high probability cloze words, low probability cloze words and incongruent words averaged over in the time interval between 330–560 ms after word onset. The electrode sites for the selected regions are circled with black rectangles.

−4.72 µV, SE 0.60 µV; posterior: −5.04 µV, SE 0.73 µV) and the center region (central: −5.01 µV, SE 0.72 µV; posterior: −4.86 µV, SE 0.77 µV) compared to the left hemisphere (central: −3.90 µV, SE 0.61 µV; posterior: −4.41 µV, SE 0.67 µV; $P<0.01$, Bonferroni *post-hoc* test). This difference gave rise to a significant CLOZE × REGION × HEMISPHERE interaction ($F_{8,152}=2.83$, MSE=0.35, $P<0.05$).

For the N400 latency values, a similar repeated measures ANOVA was calculated with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior) and HEMISPHERE (left, center, right). Peak latencies differed between regions and hemispheres which is reflected in a significant interaction of REGION × HEMISPHERE ($F_{4,76}=6.12$, MSE=732, $P<0.01$). No other effects were significant.

To investigate a possible modulation of the N400 component by L2 proficiency levels, correlations were calculated between participants' DIALANG scores with the amplitude and latency values of the N400. For amplitude values, no significant correlations were observed with DIALANG scores. It should be noted that, in the low probability cloze condition, two marginally significant negative correlations were found in the right anterior region ($r_{18}=-0.41$, $P=0.07$) and in the right central region ($r_{18}=-0.44$, $P=0.05$). For the N400 latency values, significant negative correlations with DIALANG scores were observed for the low probability cloze condition in the central regions (left: $r_{18}=-0.46$, $P<0.05$; mid-central: $r_{18}=-0.48$, $P<0.05$; right: $r_{18}=-0.47$, $P<0.05$), as well as in the posterior regions (left: $r_{18}=-0.42$, $P=0.067$; mid-posterior: $r_{18}=-0.54$, $P<0.05$; right: $r_{18}=-0.53$, $P<0.05$). For incongruent words only a marginally significant correlation was found in the left hemisphere of the parietal region ($r_{18}=-0.39$, $P=0.09$). The negative correlations indicate that a high DIALANG score was associated with a shorter N400 latency in the low cloze probability condition. A plot of the participants' DIALANG scores against the N400 latency values, averaged over all nine regions for the low cloze probability condition, is given in Figure 4. No significant correlations were observed for the high probability cloze condition or the incongruent condition. It should be noted that the high proficiency level of the participants led to a small variance in the DIALANG scores, so that correlations between N400 latency and amplitude with proficiency might be underestimated.

EEG analysis – ERD/S

The time-frequency analysis shows a relative power increase in the theta band 300 to 600 ms after the onset of the presentation of the sentence final word. The time courses and topography of relative power increases in the theta band are shown in Figure 5A and B. The averaged theta ERD/S values were entered into a repeated measures ANOVA with the factors CLOZE (high, low, incongruent), REGION (anterior, central, posterior) and HEMISPHERE (left, center, right).

The increase in relative theta power differed between conditions and location, which is reflected in a significant CLOZE × REGION × HEMISPHERE interaction ($F_{8,152}=2.86$, MSE=0.01, $P<0.05$), as well as in a marginally significant CLOZE × REGION interaction ($F_{4,76}=2.47$, MSE=0.07, $P=0.095$). Low cloze probability words showed a stronger theta increase than incongruent words at anterior, central and posterior electrode sites within the left hemisphere, as well as a

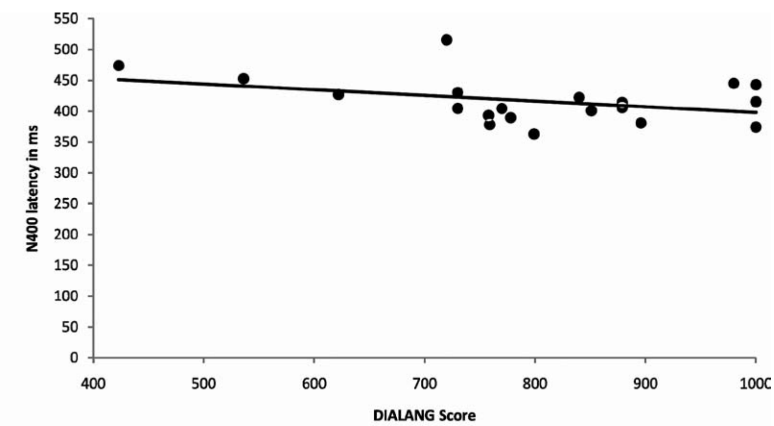

Fig. 4. A plot of the participants' DIALANG scores against N400 latency (averaged over all nine regions) in the low cloze probability condition.

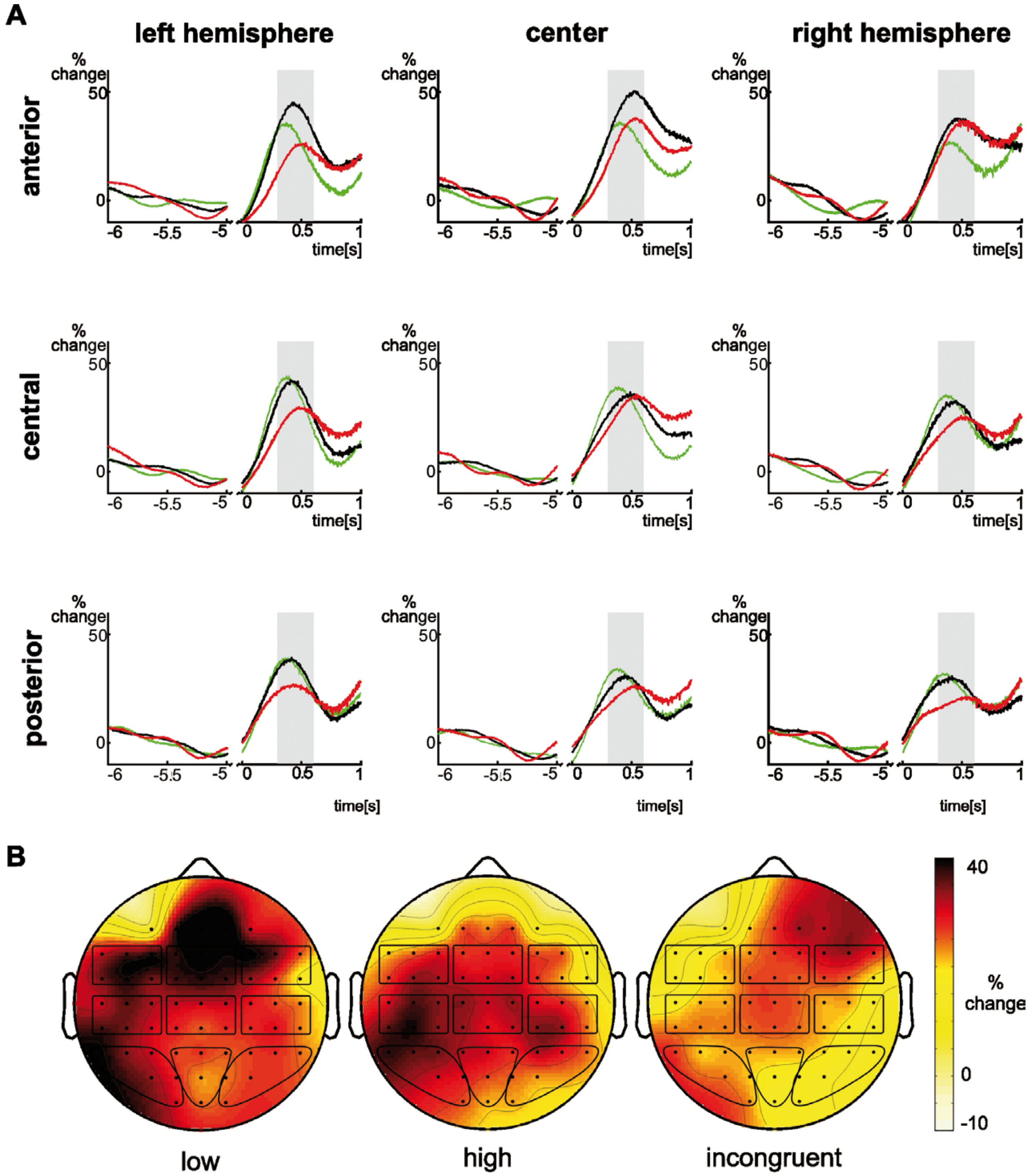

Fig. 5. Power changes (ERD/ERS) in the theta frequency band (4–7 Hz): (A) Time courses of relative theta power changes, relative to the reference period (−6 to −5 s), are given for the first second after the onset of the sentence final word, separately for each region and condition. The analyzed time window (300 to 600 ms) is indicated by a gray bar. High probability cloze words (green), low probability cloze words (black), incongruent words (red). (B) Scalp topographies of the relative theta power changes for high and low probability cloze words and incongruent words, averaged over the time interval from 300 to 600 ms after the onset of presentation of the sentence final word. The electrode sites for the selected regions are circled with black rectangles. Dark colors indicate event-related bandpower increase (ERS), light colors event-related bandpower decrease (ERD).

tendency within the right posterior region (*P*=0.051). Additionally, low probability words showed a stronger theta ERS increase in the mid-anterior than in the mid-central region. In contrast, incongruent words elicited the largest theta ERS in the right anterior region compared to the right central and right posterior region and a stronger theta ERS in the mid-anterior compared to the mid-posterior region. High cloze probability words also showed a stronger theta ERS increase than incongruent words within the left central and posterior region. A significant difference between incongruent and high cloze probability words was also observed within the right anterior region, but here a stronger theta increase was observed for incongruent words as compared to high cloze probability words. Significant differences were observed between high and low probability words within the anterior regions across hemispheres, with low probability clozes showing a stronger relative theta power increase than high probability clozes. A lateralization difference was also found, but only for incongruent words, where a stronger theta increase was observed in the right anterior and mid-anterior region than in the left frontal regions (for all comparisons: *P*<0.05, Bonferroni *post-hoc* tests).

To investigate a possible modulation of theta ERD/S by L2 proficiency levels, correlations were calculated between participants' DIALANG scores with the averaged ERD/S values for the theta frequency band. No significant correlations were observed.

DISCUSSION

In this study, we investigated the influence of proficiency on electrophysiological correlates of semantic processing in bilinguals. We presented sentences ending in high or low probability cloze words, or semantically incongruent words. Event-related potentials (ERPs) as well as the oscillatory dynamics in the EEG signal (ERD/S) were analyzed. The N400 showed a distinct modulation due to second language proficiency. Furthermore, qualitative differences between the ERP and the ERD/S results were observed, indicating that the two types of analysis possibly tap different processes in sentence comprehension.

Our results with regard to the N400 component in all three conditions match well previously reported results. Incongruent words elicited a larger N400 than words with a low cloze probability followed by words with a high cloze probability. The N400 has been observed to be highly sensitive to the expectability of a word with N400 amplitude being inversely related to the cloze probability of a word (Kutas and Hillyard 1984). The N400 topography observed in the present study also showed a clear centro-parietal maximum, which is typical for visually presented words (Domalski et al. 1991). Previous studies also showed that the N400 is a robust correlate of the semantic processing of words in sentences, as it was observed for different modalities (auditory or visually presented words), and for sentence final words as well as for words within a sentence (Kutas and Federmeier 2000). With regard to lateralization, we also found a larger N400 amplitude in the right hemisphere for incongruent words only. This result is similar to the findings of Proverbio and coauthors (2004), who interpreted this result as reflecting a greater sensitivity of the right hemisphere to semantic violations. In the present study, we found that the bilinguals we tested were sufficiently proficient in their second language and behaved similar to native speakers with regard to the N400 amplitudes in the three conditions.

The N400 component observed here was modulated by the participants‘ second language proficiency. We observed a significant negative correlation between the participants‘ DIALANG scores and the N400 latency for the low cloze probability condition. Our results are in line with previous results on bilinguals (Ardal et al. 1990), where a longer N400 latency was observed for L2 compared to L1. The specific correlations between L2 proficiency and N400 latency in the low cloze probability condition observed here might indicate that less proficient bilinguals take longer to process unexpected words. There was only a marginally significant correlation between proficiency and incongruent words. The significant negative correlation between L2 proficiency and N400 latency in the low cloze probability condition could reflect the specific difficulty to integrate an unexpected word into a meaningful conceptual representation of the sentence. This is possible for words with high and low cloze probability but not for incongruent words. The comparatively high error rate in the low close probability condition also suggests that the participants had specific difficulties in the low cloze condition. As properties on word level were similar in all three conditions, these difficulties have to consist in integrating an unexpected word into a meaningful conceptual representation of the sentence, whereas the implausibility of a sentence might have been recognized early on the presentation of an incongruent word. We did not observe a modulation of L2 proficiency on the error rates or on the amplitude of the N400. One reason for the small number of observed correlations might be the low variance of the overall proficiency level of our participants. It was comparatively high and homogeneous (See Fig. 4). It should be noted, however, that our finding of a modulation in N400 latency by L2 proficiency but not N400 amplitude at posterior sites are in agreement with the results from other studies. (i.e., Ardal et al. 1990). Age of acquisition was also observed to influence N400 latency. Weber-Fox and Neville (1996) found a longer N400 latency rather than amplitude or topography differences for late bilinguals (age of L2 acquisition >10 years) compared to early bilinguals. Similarly, Moreno and Kutas (2005) observed for bilinguals a positive correlation of N400 latency with age of acquisition. The correlation between the N400 latency in the low cloze probability condition and L2 proficiency suggests that access to meaning improves in late L2 learners. All our participants were late L2 speakers. According to the revised hierarchical model of lexical access in bilingualism by Kroll and Stewart (1994), L2 processing is similar to L1 processing rather than different. L2 words and their concepts are only connected by weaker links than L1 words and their concepts (Kroll and Stewart 1994, for a review, see Mueller 2005). The strength of links between L2 words and their concepts has been observed to depend strongly on the age of L2 acquisition (Kotz 2001, Kotz and Elston-Guettler 2004). Our finding of a correlation between the N400 latency in the low cloze probability condition and L2 proficiency also suggests that, regardless of the difficulties of L2 acquisition, the processing of L2 is more similar to rather than different from the processing of L1.

Interestingly, the results pattern of the theta ERD/S analysis seems to reveal a different picture than the ERP analysis. In the present study, the ordering of conditions with regard to the size of the relative theta power increase on the presentation of the sentence final word differs from the N400 results. While the incongruent condition led to the highest N400 amplitude, in the ERDS results, high and low cloze probability words yielded a stronger increase in relative theta power than incongruent words. These results fit well with previous studies. A study by Bastiaansen and colleagues (2005) observed a stronger theta power increase for open class words as compared to closed class words during attentive reading of visually presented sentences. Open class words are primary carriers of meaning within a sentence such as verbs, nouns, adjectives, whereas closed class words serve primarily syntactically (e.g., ‚is‘, ‚and‘). The stronger increase in theta over temporal regions for the open class words as compared to closed class words was interpreted by the authors as being related to retrieving the meaning of the words from long-term memory. Moreover, the increase in theta power while processing sentences is possibly related to the formation of an episodic memory trace, or to incremental verbal working memory load (Bastiaansen et al. 2002). It is possible that sentences ending with a high or low cloze probability word yield a stronger increase in theta power because here a conceptualization of the sentence is possible. Conceptualization means the formation of a meaningful idea that can be stored as one unit in memory. It is therefore very plausible that the ERD/S reflects working memory operations, be it encoding or retrieval. Bastiaansen and others (2002) also observed that theta power continuously increased during the processing of a sentence, also consistent with the online generation of a conceptual representation of the sentence. The sensitivity of both measures to semantic processes and their differences with regard to function and topography observed by us fits well with previous results. For example, Bastiaansen and coworkers (2008) observed clear differences between the functional properties and topographies of the N400 and theta power in an experiment comparing words associated with visual properties (e.g. “square”) and words with auditory properties (e.g. “scream”). In a recent study by Maguire and colleagues (2010), differences were found between different types of semantic priming (associative vs. categorical) in theta power but not with regard to the N400. It should be noted however, that our results do not fit well with the results of Hald and others (2006): they observed a stronger theta increase for semantically incorrect sentences (e.g., ’The Dutch trains are SOUR and blue.‘) compared to correct sentences (e.g., ‚The Dutch trains are YELLOW and blue.‘). Similarly, Hagoort and coworkers (2004) observed a stronger theta increase for semantically incorrect sentences compared to sentences that violated world knowledge (e.g., ‚The Dutch trains are WHITE and very crowded.‘), or correct sentences (e.g., ‚The Dutch trains are YELLOW and very crowded.‘). It is unclear, why no increase in theta power was observed for the meaningful sentences in these studies. One possible difference could be the task employed. In our study, participants had to perform an acceptability judgment whereas Hald and colleagues (2006) had only instructed their participants to read the presented sentences. It should be noted that, to date, only a small number of studies have evaluated induced theta activity in language. To our knowledge, no study has investigated induced theta activity for different levels of cloze probability.

Differences between the N400 and the ERD/S are also obvious with regard to the topography. Whereas the N400 shows a rather uniform centro-parietal distribution, the topography of the theta ERD/S shows a more diverse pattern. For the low and high cloze probability condition, the ERD/S theta topography shows a strongly left lateralized relative power increase over temporo-parietal regions, compared to the incongruent condition. For the incongruent condition, a stronger right-lateralized relative power increase is observed over the right frontal lobe.

Both hemispheres are involved in semantic processing but in a different way: The left hemisphere is assumed to be involved in written word recognition and in lexical decisions whereas the right hemisphere appears to be dominant for mainly semantic functions in language production (Taylor and Regard 2003). The right hemisphere also seems to process semantic information more slowly and less focused than the left hemisphere (Taylor et al. 1999)

The difference between theta power and N400 topographies suggests that the relative theta power increase might be due to two different processes. The synchronization within the anterior part of the right hemisphere for the incongruent condition might be related to the relative general unexpectedness of the sentence final word, when compared to the high cloze probability condition. The relative power increase within the left temporo-parietal region for high and low cloze probability words as compared to incongruent words, on the other hand, might reflect semantic integration and the possibility to create a meaningful conceptual representation of the sentence.

It is yet unclear, whether or how a relative theta power increase measured over a certain brain area can be related to the brain activity or oxygenation in this area. Although it is assumed that relative power changes arise from local changes in neural synchronization, this assumption has not yet been tested directly. It should be noted, however, that fMRI studies comparing meaningful with meaningless sentences often find stronger temporo-parietal activation for meaningful sentences (Humphries et al. 2006, 2007). Similar to the present study, Humphries and coworkers (2006, 2007) also used an acceptability judgment. These results fit well with our finding of a stronger relative theta power increase in left temporo-parietal brain areas for the congruent (low and high cloze probability) conditions than for the incongruent condition. An fMRI study by Dien and coauthors (2008) compared sentences ending in words with different cloze probabilities and incongruent words. For incongruent words stronger activation than for high and low cloze probability words was observed within the left dorsolateral prefrontal cortex and words with low cloze probability activated a region within the posterior inferior temporal gyrus more strongly than words with high cloze probability. The results of this study, however, are difficult to directly compare to our study as Dien and others (2008) did not report the comparison of the congruent (high and low probability cloze words) conditions against the incongruent condition.

CONCLUSION

Both the N400 and theta ERS have been associated with the processing of meaning, the different results observed for both suggest that the N400 and relative theta power changes represent different types of semantic processing. Although more research is required to clarify the role of theta ERS in semantic processing the present results seem promising in further elucidating the complex processes involved in the access to meaning in language.

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APPENDIX

Full listing of the stimulus materials. The sentence final words are printed in capital letters, in the following order: high cloze probability/low cloze probability/incongruent words.

1. Our new green car blocked the narrow DRIVEWAY/ENTRANCE/ELBOW.
2. To tune your car you need a special TOOL/KIT/FARM.
3. The surgeon tried vainly to save his PATIENT/SON/ANSWER.
4. Fred put the worm on a HOOK/TABLE/KINGDOM.
5. She called her husband at his OFFICE/JOB/DOVE.
6. The children held their hands and formed a CIRCLE/LINE/RESCUE.
7. Ira turned on the radio and listened to the MUSIC/TUNES/HAIR.
8. The thick mud stuck to her SHOES/FACE/BATHROOM.
9. The movers put the sofa on the bare FLOOR/GROUND/FOG.
10. Scotty licked the bottom of the BOWL/STAMP/FIRE.
11. He loosened the tie around his NECK/COLLAR/LASH.
12. Ray fell down and skinned his KNEE/NOSE/SHELL.
13. The girl was advanced for her AGE/GRADE/FUTURE.
14. Autumn is a good time to buy some new CLOTHES/BOOTS/GRANDMA.
15. Starting a business takes a lot of MONEY/PATIENCE/POEM.
16. He bought them in the candy STORE/MACHINE/TREE.
17. The old house was built entirely of WOOD/STONE/BODIES.
18. It’s easy to get lost without a MAP/GUIDE/ROOM.
19. Yesterday they canoed down the RIVER/LAKE/EYE.
20. She tied up her hair with a yellow RIBBON/BOW/LAW.
21. Her new shoes were the wrong SIZE/COLOR/LEAVE.
22. Bob thought she had such a friendly SMILE/NEIGHBOR/HONEY.
23. The winter was very harsh this YEAR/TIME/SHIP.
24. Most shark attacks occur very close to the SHORE/LAND/RISK.
25. They took short trips during the SUMMER/VACATION/HOPE.
26. During class Jack had to borrow some PAPER/NOTES/GAINS.
27. He scraped the cold food from his PLATE/DISH/FLOWER.
28. After dinner they washed the DISHES/CAR/MOON.
29. During the volley, Joe twisted his ANKLE/KNEE/RICE.
30. George must keep his pet on a LEASH/DIET/PRIEST.
31. Her job was easy most of the TIME/DAY/CARE.
32. Betsy could never tell a LIE/JOKE/NOON.
33. The child was born with a rare DISEASE/GIFT/CITY.
34. Not even the cast liked the PLAY/STORY/ESTEEM.
35. The bill was due at the end of the MONTH/HOUR/IDEA.
36. New York is a very busy CITY/PLACE/EAR.
37. The man was caught selling an illegal DRUG/WEAPON/RAINBOW.
38. Jack bet all he had on the last RACE/HORSE/HAM.
39. The rider walked his beautiful HORSE/BICYCLE/HOSPITAL.
40. At each table, I had to fill in another FORM/GLASS/ISLAND.
41. Dillinger once robbed that BANK/TRAIN/SCAR.
42. After speaking Allen left the noisy ROOM/CLASS/UMBRELLA.
43. The mole lived in a hole in the GROUND/VALLEY/BIT.
44. None of his books made any SENSE/MONEY/BRIDE.
45. The boys were given hamburgers for LUNCH/REWARD/NUMBER.
46. He liked lemon and sugar in his TEA/COFFEE/ELEPHANT.
47. Their picnic was ruined by the RAIN/ANTS/AGE.
48. The governor vetoed the new BILL/LAW/SILENCE.
49. Jill looked back through the open DOOR/GATE/BED.
50. The fertilizer enriched the SOIL/PLANTS/TENT.