Brain potentials indicate immediate use of prosodic cues in natural speech processing

Karsten Steinhauer, Kai Alter and Angela D. Friederici

Department of Neuropsychology, Max Planck Institute of Cognitive Neuroscience, PO Box 500 355, D-04303 Leipzig, Germany

Correspondence should be addressed to K.S. (steinhau@cns.mpg.de)

Spoken language, in contrast to written text, provides prosodic information such as rhythm, pauses, accents, amplitude and pitch variations. However, little is known about when and how these features are used by the listener to interpret the speech signal. Here we use event-related brain potentials (ERP) to demonstrate that intonational phrasing guides the initial analysis of sentence structure. Our finding of a positive shift in the ERP at intonational phrase boundaries suggests a specific on-line brain response to prosodic processing. Additional ERP components indicate that a false prosodic boundary is sufficient to mislead the listener's sentence processor. Thus, the application of ERP measures is a promising approach for revealing the time course and neural basis of prosodic information processing.

Human everyday communication is spoken rather than written, but the overwhelming majority of psycholinguistic research underlying models of sentence processing is still based on reading rather than speech-processing data. One reason for this asymmetry is that written text, as compared to spoken language, can be much more easily controlled in experimental design. Natural speech is always 'contaminated' with prosodic features, which increase word-length variability and introduce pitch and amplitude variations; these variables can be completely avoided with written text. Prosodic features, however, may be important for communication, and some studies on spoken language suggest that prosodic information may influence sentence processing to such a degree that preferences observed during reading may not apply equally to speech processing[1–3]. For example, eye-tracking measures in a reading task indicate[4] that sentence 1a is much easier to understand than sentence 1b:

(1a) Since Jay always jogs <u>a</u> <u>mile</u> <u>and</u> <u>a</u> <u>half</u> this seems like a short distance to him.
(1b) Since Jay always jogs <u>a</u> <u>mile</u> <u>and</u> <u>a</u> <u>half</u> seems like a very short distance to him.

Initially, the reader prefers to interpret the noun phrase "a mile and a half" as the grammatical object of the preceding verb "jogs" rather than as the subject of the subsequent verb "seems", as required in 1b. Thus the initial analysis must be revised in 1b, which results in a prolonged reading time, a phenomenon called the 'garden-path effect'.

The robustness of such effects in reading studies led to the development of the garden-path model of sentence processing[4]. According to this model, initial preferences are exclusively attributed to the inherent processing principles of an encapsulated syntactic processing system (called syntactic parser), which cannot be influenced by non-syntactic information[5]. Semantic interpretation (or 'meaning') occurs only once the syntactic parsing of grammatical relations has been accomplished. Psycholinguists have long debated whether or not the initial syntactic preferences can be immediately overridden by non-syntactic influences such as semantic or pragmatic cues[6,7]. When non-syntactic influences have been found, the temporal immediacy of these effects has been controversial[5]. When sentences such as 1a and 1b are presented auditorily, the initial preference in favor of 1a is considerably diminished by a prosodic boundary after the first verb[2]. This finding suggests that prosodic information does influence decisions about syntactic structure at very early stages.

However, little is known about the exact relationship between prosody and sentence processing, and in particular the time course and neural basis of influences such as the one just described[8,9]. Event-related brain potentials (ERPs) are a useful tool for the on-line examination of both normal and impaired language processing[10,11], which may contribute to the development of theoretical accounts of prosodic and syntactic interaction. The ERP correlates of initial syntactic misanalyses for both written and spoken presentation show that the additional costs are reflected by a late posterior positivity between 500 and 1200 ms (termed the P600 component or 'syntactic positive shift')[12–15]. In contrast, difficulties of lexical and semantic processing (for example, "He spread the warm bread with socks") generally elicit an earlier centroparietal negativity between 300 and 900 ms (the N400 component)[16–19] rather than a P600. These two classes of ERP effects indicate specific brain responses to different linguistic features. Here we used ERP measures for the on-line investigation of prosodic features.

We examined the influence of prosody on human parsing performance with both behavioral and neurophysiological (ERP) measures. The stimulus material consisted of spoken German sentence pairs similar to the English examples in 1a and 1b. To establish controlled experimental conditions comparable to those in reading studies, we needed exhaustive acoustic analyses of the speech signals. These analyses revealed systematic prosodic dif-

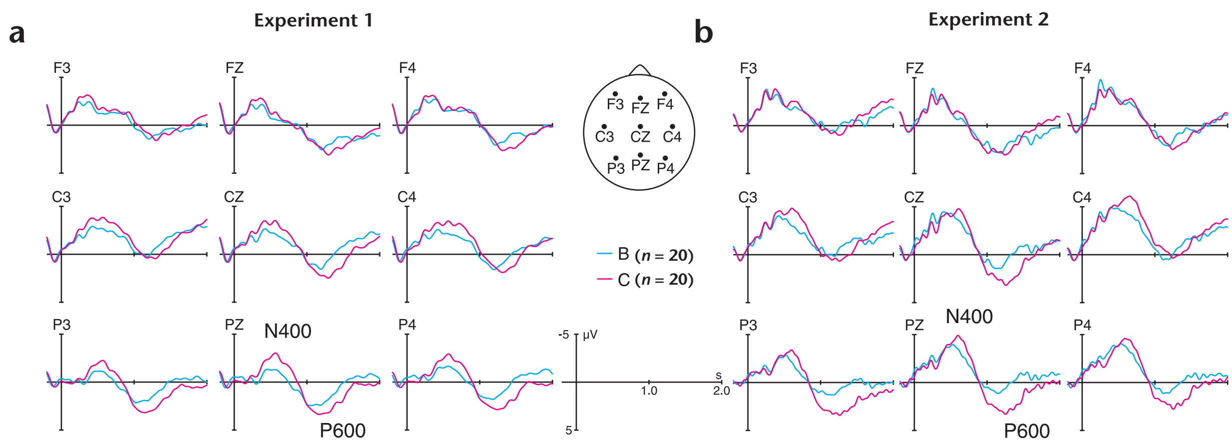

Fig. 1. Prosody–syntax mismatch. ERPs of conditions B (blue) and C (red) at nine electrodes from the onset of the infinitive marker "zu" of the critical second verb until two seconds later, displayed separately for each experiment. Negative amplitudes are plotted upwards. **(a)** In Experiment 1 (*n* = 20), the prosody–syntax mismatch condition C is characterized by an N400 component followed by a P600. **(b)** In Experiment 2 (*n* = 20), the same biphasic N400–P600 pattern as in Experiment 1 was elicited in condition C.

ferences between the two conditions, suggesting a specific prosodic phrasing and accentuation pattern dependent on the syntactic structure. When the sentences were presented auditorily, the listener's event-related brain potentials reproducibly showed a characteristic positive-going waveform at prosodic phrase boundaries, indicating immediate decoding of this information. Furthermore, in a third condition, we introduced the initial prosodic features of one condition into the other condition, leading to a prosody–syntax mismatch. Both behavioral and ERP data strongly suggest that the prosodic features determined the initial parsing decisions. The mismatch between prosody and syntax was reliably detected by the listeners and elicited an N400–P600 pattern of ERP components reflecting a prosody-induced garden-path effect.

Results

The German sentence material consisted of 48 sentence pairs such as 2a and 2b, where the bracketing indicates the respective intonational phrases (IPhs)[20] as described below:

(2a) [Peter verspricht Anna zu arbeiten]$_{\mathrm{IPh1}}$ [und das Büro zu putzen]$_{\mathrm{IPh2}}$
Peter promises Anna to work and to clean the office

(2b) [Peter verspricht]$_{\mathrm{IPh1}}$ [Anna zu entlasten]$_{\mathrm{IPh2}}$ [und das Büro zu putzen]$_{\mathrm{IPh3}}$
Peter promises to support Anna and to clean the office

As in example 1a, the noun phrase "Anna" is the object of the first verb "verspricht" ("promises") in 2a and therefore belongs to the first IPh. In contrast to 2a but similar to 1b, in sentence 2b "Anna" is the object of the second transitive verb "entlasten" ("support") and belongs to the second IPh. Because of the German word order, the correct interpretation of "Anna" is syntactically disambiguated by the second verb only (that is, "arbeiten" ("work") in 2a versus "entlasten" in 2b). Compatible with the predictions of certain theories of syntax–prosody mapping[21,22], however, the 48 speech signals of conditions 2a and 2b differ considerably even before the point of syntactic disambiguation, via different intonational phrasing and accentuation (Methods).

Our hypothesis was that these early prosodic differences of spoken language could be sufficient to prevent the garden-path effect in 2b. If the additional IPh boundary indeed changes the initial interpretation of "Anna", then it should even be possible to reverse the garden-path effect. That is, if the early prosodic cues of 2b were introduced in sentence 2a, we expected an initial misanalysis and garden-path effect in this normally easy-to-process structure. The noun phrase "Anna" would then be erroneously attached to the second verb, which is intransitive and cannot take a direct object as its argument. Using a cross-splicing technique[23], we merged the acoustic signals of the first part of 2b and the second part of 2a between "Anna" and the infinitive marker "zu" ("to") of the second verb in each of the 48 sentence pairs. This resulted in a third condition (2c) with a mismatch

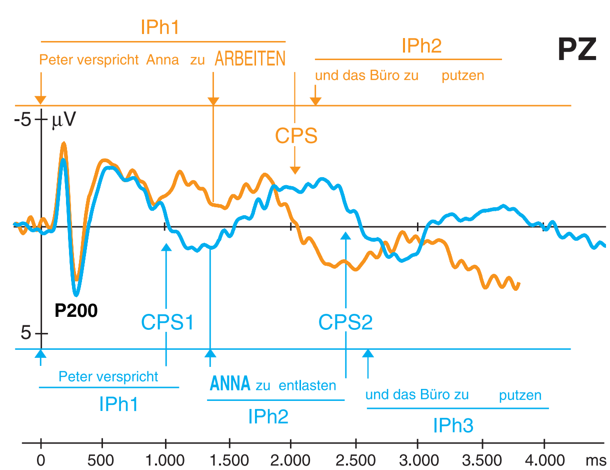

Fig. 2. Closure positive shift. Grand-average ERPs of both experiments (*n* = 40) at the PZ electrode. The waveforms of conditions A (orange) and B (blue) are superimposed. The word onsets of the sentence examples are aligned to the time axis. Both conditions evoke closure positive shifts at their respective IPh boundaries. Only one shift is observable in condition A, following the second verb "arbeiten", whereas two such shifts occur in condition B, before "Anna" and after the second verb "entlasten".

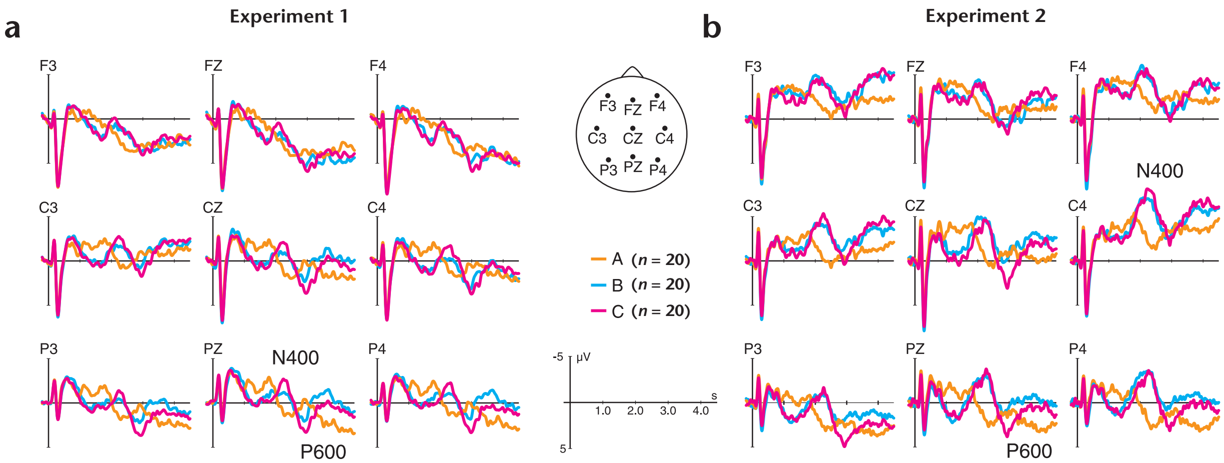

Fig. 3. Sentence-specific ERPs. ERPs of all three conditions at nine electrode sites from sentence onset until four seconds later, plotted separately for each experiment. **(a)** In Experiment 1 (n = 20), conditions B (blue) and C (red) share the same pattern of two CPSs as opposed to one CPS in condition A (orange). By two seconds, that is, after onset of the second verb, the prosody–syntax mismatch condition C diverges from B and elicits the N400–P600 pattern. **(b)** Experiment 2 (n = 20) generally replicates the findings of Experiment 1.

between prosodic information (Methods) and syntactic constraints (that is, the intransitivity of the verb "arbeiten"):

(2c) * [Peter verspricht]$_{IPh1}$ [Anna zu arbeiten]$_{IPh2}$ [und das Büro zu putzen]$_{IPh3}$
Peter promises to work Anna and to clean the office

The prosodic inappropriateness of 2c becomes obvious only when the intransitive verb "arbeiten" is encountered. At this point, the sentence should initially be perceived as "Peter promises to work Anna", which is certainly ungrammatical and requires revision. According to linguistic convention, ungrammatical sentences are marked by an asterisk.

Forty-eight sentences of each of the three conditions were presented to 40 subjects in two ERP experiments varying in their task requirements: comprehension task (Experiment 1) and prosody judgment plus comprehension task (Experiment 2). The prosody acceptability judgment revealed that the participants reliably detected the prosody–syntax mismatch in condition C. In this condition, only 6% of the trials were rated as acceptable, as opposed to more than 80% in both conditions 2a and 2b ($p < 0.0001$). The error rates in the comprehension task were not significantly increased in the mismatch condition (C) for either Experiment 1 or 2.

We focused on two questions: first, whether and how ERPs reflect the influence of prosodic information on early syntactic processes, and second, whether ERPs are sensitive to the processing of prosodic features *per se*. We briefly discuss the effect indicating the interplay between syntax and prosody and then turn to a newly identified prosody-related ERP component. As Experiments 1 and 2 had very similar results, they are presented jointly.

The syntax–prosody mismatch effect

In reading studies using ERPs, violations of a verb's argument structure elicit an N400 component followed by a P600 component[14,24]. As predicted, we found a similar biphasic N400–P600 sequence during the intransitive second verb for condition C as compared to the grammatically correct transitive verb in condition B (**Fig. 1**). Mean amplitude analyses across 8 consecutive 200-ms time windows (from 200 to 1800 ms) confirmed that both effects were restricted to centroparietal electrodes. The N400 effect was significant between 400 and 1000 ms ($p < 0.01$) and the P600 effect between 1200 and 1800 ms ($p < 0.001$). For both ERP components, we observed only main effects of the sentence condition (condition B versus C) and no further interactions with the task factor. Baseline-independent, peak-to-peak measures including condition A ruled out the possibility that the effects were simply due to the different verbs (transitive verbs in B versus intransitive verbs in C). Although condition A contained the same intransitive verbs as condition C, the amplitude difference between the N400 peak and the P600 peak in condition A was significantly

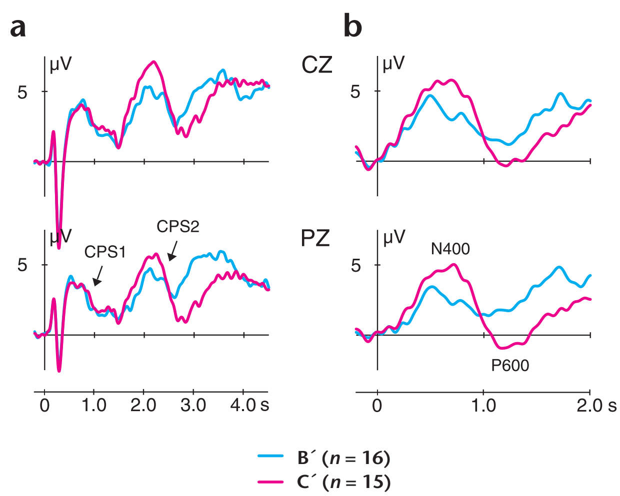

Fig. 4. ERPs after pause removal. ERPs of conditions B′ (blue) and C′ (red) in Experiment 3 (n = 16) at the CZ and PZ electrode sites. **(a)** Even after removal of the pause between the first verb and the second noun phrase, both conditions still display the CPS at the first IPh boundary. **(b)** As in the first two experiments, the intransitive verb of the prosody–syntax mismatch condition C′ elicits a biphasic N400–P600 pattern. This comparison is more reliable than that in Fig. 4a, as the average window is aligned to the critical verb and more trials entered the averages.

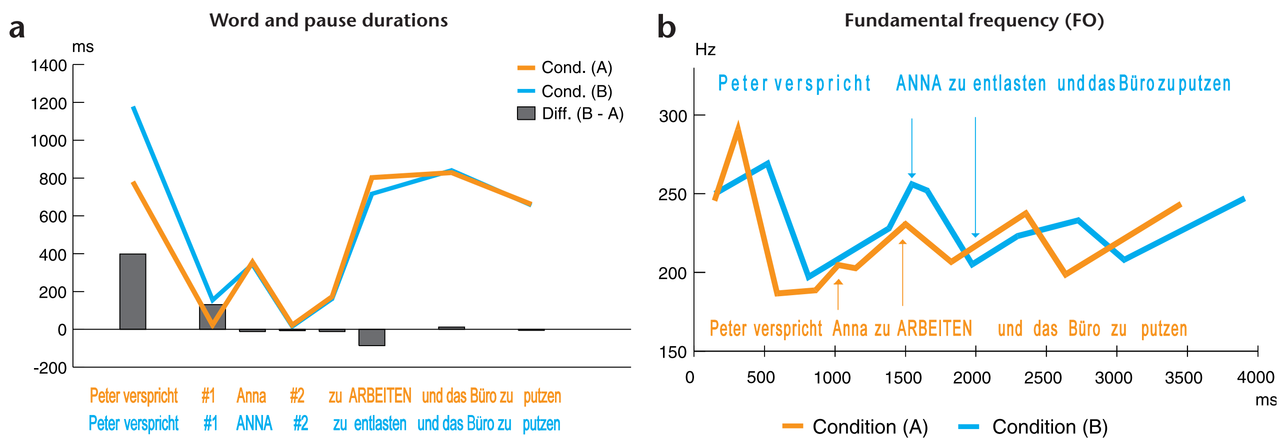

Fig. 5. Prosodic parameters. Prosodic differences between the speech signals of conditions A (orange lines) and B (blue lines). **(a)** Duration measures of sentence fragments and pauses (#) and respective differences between conditions B and A. Condition B shows both a lengthening of the first sentence fragment "Peter verspricht" ($p < 0.0001$) and a subsequent pause insertion (#1; $p < 0.0001$). **(b)** Fundamental frequency. Whereas the main pitch accent in condition A is on the verb "arbeiten", it is aligned to the noun phrase "Anna" in condition B. Because of the lengthening in B, however, both accents occur at approximately the same time.

smaller than that in C ($p < 0.005$), and it did not differ from B ($F < 1$). Thus the increased N400 and P600 amplitudes in condition C were not due to either the verb or the prosodic pattern *per se* but rather to the mismatch between the two.

An ERP component reflecting prosodic processing

The prosodic processing that induced the reversed garden-path effect was also reflected in the ERPs. In both experiments, we found a large positive waveform at intonational phrase boundaries. The grand-average ERPs across both experiments ($n = 40$; **Fig. 2**) showed that condition A evoked a single shift at its IPh boundary following the second verb. The ERP for condition B, in contrast, contained two such positive shifts, corresponding to its two IPh boundaries, the first one preceding "Anna" and the second after the second verb. This pattern of one versus two positive shifts was confirmed statistically by both amplitude comparisons ($p < 0.001$) and peak localizations ($p < 0.0001$) and did not differ between Experiment 1 (**Fig. 3a**) and Experiment 2 (**Fig. 3b**; $F < 1$). Moreover, the ERP for the mismatch condition C, which contains two IPh boundaries, also had the two corresponding shifts (**Fig. 3**). Additional analyses revealed that the positive shift at IPh boundaries was not due to the word preceding each IPh boundary being a verb or to so-called exogenous ERP components (such as N100 or P200) reflecting the physical features of the stimulus. As we assume that the shift primarily reflects the closure of an intonational phrase, we term this ERP component the 'closure positive shift' (CPS).

An important question is whether the CPS actually reflects prosodic phrasing or whether it is more directly related to the acoustic properties marking the boundary. Because in written sentences terminal words preceding a pause are also associated with positive ERP components[25,26], the most likely candidate for such direct correspondence is the pause insertion after the first verb in conditions B and C, that is, the temporary absence of any speech input at the boundary. Therefore, we ran a third ERP experiment in which we carefully removed the entire pause in both conditions B and C, preserving other intonational cues. Behavioral and ERP results for these new conditions B′ and C′ confirmed that even without the pause the prosodic boundary was still perceived by the listeners ($n = 16$) and guided their initial parsing decisions (prosodic acceptability rates, 73.8 % in B′, 10.9 % in C′). We still observed the CPS at the first boundary and also the N400–P600 effect in condition C′ (**Fig. 4**). This finding supports the idea that the CPS reflects the processing of the prosodic boundary rather than the perception of a pause interrupting the speech input.

Discussion

The present study tested whether prosodic cues in spoken language are immediately used by the listener to solve syntactic ambiguities that systematically result in initial misunderstandings during reading, and to determine whether these prosodic influences can be monitored on-line by ERP measures. Not only did we demonstrate that the prosodic information was sufficient to reverse syntactic parsing preferences, but we also identified a specific ERP component reflecting the decoding of intonational phrasing, the closure positive shift.

With respect to psycholinguistic modeling, the data provide strong evidence that the syntactic parser can be directly influenced by prosodic information. The presence of an early IPh boundary preceding "Anna" in conditions B and C stopped further syntactic integration into the current first verb phrase and instead prepared an initial attachment of "Anna" to the second verb. This reversed parsing preference, triggered exclusively by prosodic information, successfully induced an initial misanalysis (a garden-path effect) in the mismatch condition C and elicited the predicted N400–P600 pattern of ERP components on the incompatible intransitive verb. The cognitive processes underlying both components are still subject to discussion[27]. Here we follow a recent interpretation[28] according to which the N400 effect presumably reflects a lexical re-access necessary to confirm the outright violation of the intransitive verb argument structure in condition C[29]. The P600, on the other hand, seems to indicate the subsequent structural revision concerning the attachment site of "Anna". The rapidity of this on-line revision would also explain why we did not find any increased error rates in the comprehension task. When the question was presented one second later, the structure had already been repaired. As the repair process is very likely to involve subvocal corrections of the intonational phrasing, we assume that the P600 component may reflect the costs of both syntactic and prosodic revisions.

We also found that prosodic boundaries are associated with a large positive-going waveform, which we labeled the closure positive shift (CPS). This component did not depend on the presence or absence of a pause acoustically interrupting the stream of speech input. Rather, whenever the boundary was perceived and used to guide parsing, the CPS was found in the corresponding time interval. The CPS may be associated with processes that serve to structure the mental representation of the speech signal and to prepare the further analysis of subsequent input. It seems that, at least for the sentences used in the present study, the CPS enables monitoring of prosodically driven parsing decisions long before the syntactically disambiguating element (the second verb) is encountered.

Because of the confound between prosodic and syntactic units in natural language, the present data leave open whether the CPS is predominantly related to prosodic structuring *per se* or to its consequences on syntactic processing. Our recent ERP study using auditorily presented artificial language (unpublished data), however, seems to support the view of prosodic processing underlying the CPS. On reinspection of this data to replicate our CPS finding, a CPS was observed even in a group of naive subjects who had not yet acquired the syntax rules of the artificial language. Syntactic ERP effects, in contrast, were found only in participants who were already familiar with the syntax rules (E. Pfeifer & A.D.R., *J. Cogn. Neurosci. Suppl.*, p. 26, 1998).

Whereas the question of which prosodic cues are necessary or sufficient to elicit a CPS requires future research, available data indicate that the component is tightly linked to the cognitive process of structuring the incoming speech signal. If this finding holds, the component may serve as a valuable tool for systematically exploring the relationship between 'prosodic parsing' and syntactic parsing, which has received little attention until recently[30–32].

Our data provide strong evidence that many garden-path effects consistently observed during reading simply may not occur in spoken language processing. This finding would be compatible with so-called 'syntax-first' models such as the garden-path model only if prosodic information is taken to directly transmit syntactic information. In any case, it underlines the necessity to take prosodic processing into account more explicitly. On-line measures such as the CPS may help to lay the empirical foundations for an adequate theory of natural speech processing. The present study is only a preliminary step toward understanding the brain functions underlying prosodic processing. However, our data strongly suggest that ERP measures used in a controlled experimental design are a promising on-line approach to shed new light on the role of prosody with regard to both normal and impaired speech processing[33].

Methods

Subjects. Twenty students participated in each of the first two ERP experiments, and sixteen in the third experiment. All 56 subjects were right-handed[34], and without hearing or neurological disorders. All three experiments complied with German legal requirements.

Speech signals. Forty-eight sentence pairs such as 2a and 2b were produced by a female native speaker of standard German and recorded in a soundproof chamber. The digitized speech signals (44.1 kHz/16 bit sampling rate) of each sentence were measured with respect to word and pause durations, fundamental frequency (pitch contour) and loudness (amplitude squares), and the differences were statistically analyzed in paired *t*-tests or with ANOVAs. There were highly significant durational differences between conditions A and B (**Fig. 5a**). The additional IPh boundary in condition B was signified prosodically by a pause insertion before "Anna" ($p < 0.0001$), as well as by a significant lengthening of the first constituent, "Peter verspricht" ($p < 0.0001$). Whereas a major accent occurred on the verb "arbeiten" in condition A, accentuation was shifted to the noun phrase "Anna" in condition B. These differences in accent positions were confirmed both by a locally rising pitch contour in the fundamental frequency ($p < 0.0001$; **Fig. 5b**) and by a corresponding loudness maximum ($p < 0.01$; not shown).

Condition C was derived by cross-splicing the first part of B and the second part of A in the silent phase of the affricate /ts/ of the infinitival marker "zu" ("to"). This procedure plus an amplitude normalization protected against detectability of the signal manipulation at the splicing point. Conditions B′ and C′ of the third experiment were obtained by removing the pause before the second noun phrase, without affecting the signals of adjacent words.

Procedure. The 144 experimental sentences were intermixed with 144 filler sentences and presented auditorily in a pseudo-randomized order in 8 blocks of 36 trials, distributed over 2 sessions. Block order was counterbalanced across subjects. EEG was continuously recorded (250 Hz/12 bit sampling rate; Neuroscan DC amplifier) from 17 cap-mounted tin electrodes while subjects listened to the sentences in a electromagnetically shielded chamber. All electrodes were referenced against left mastoid. Impedances were kept below 5 kΩ. In Experiment 1, the task was to answer yes or no to comprehension questions such as "Does Anna promise to clean the office?" in 20% of the trials. In Experiments 2 and 3, participants were asked to judge the prosodic adequacy of each sentence immediately after presentation in addition to the comprehension task.

Data analyses. EEG epochs containing eyeblinks or movement artifacts were rejected and did not enter the ERP averages. Averages were computed both across the whole sentence (**Figs. 2, 3** and **4a**) and for the critical second verb (**Figs. 1** and **4b**) using a 200-ms prestimulus baseline. The mean amplitudes of 8 subsequent 200-ms time windows were computed from 200 ms after the onset of verb 2 until 1800 ms thereafter to measure the N400 and P600 components in conditions B and C. Comparisons including condition A required additional baseline-independent peak-to-peak measures[35] to balance the diverging CPS patterns. The closure positive shift was quantified by two different approaches. First, we compared mean amplitudes across eight subsequent 500-ms time windows covering the whole sentence length. Second, we evaluated the onset and offset latencies of large positive shifts at midline electrodes separately for each subject in each condition using peak-to-peak measures. Both behavioral and ERP data were statistically tested by ANOVAs. ERP analyses were generally done separately for midline and lateral electrodes. For the midline, a global three-way ANOVA with factors conditions (3) × electrode (3) and the between-subject factor task (2) was used. For the lateral electrodes, regions of interest were defined. The resulting ANOVA design included the factors conditions (3) × hemisphere (2) × position (3) × task (2). Single comparisons were only computed if the global ANOVA revealed a significant main effect of condition with df > 1 or an interaction with the factor condition. Where appropriate, Huynh and Feldt corrections[36] and a modified Bonferroni correction procedure[37] were applied. For illustrative purposes only, the grand-average ERPs were smoothed off-line using a 5-Hz lowpass filter.

Acknowledgements

We appreciate the comments of Lee Osterhout and Gerry Altman on an earlier version of the manuscript. We also thank Katja Kühn, Annett Schirmer and Franziska Kopp for their assistance in generating the stimulus materials and in analyzing the signals. This work was supported by the Deutsche Forschungsgemeinschaft (FR 519/17-1).

Received 10 August; accepted 16 December 1998

1. Marslen-Wilson, W. S. *et al.* Prosodic effects in minimal attachment, *Q. J. Exp. Psychol.* **45A**, 73–87 (1992).

2. Warren, P., Grabe, E. & Nolan, F. Prosody, phonology, and parsing in closure ambiguities. *Lang. Cogn. Processes* **10**, 457–486 (1995).
3. Stirling, L. & Wales, R. Does prosody support or direct sentence processing? *Lang. Cogn. Processes* **11**, 193–212 (1996).
4. Frazier, L. & Rayner, K. Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cogn. Psychol.* **14**, 178–210 (1982).
5. Frazier, L. in *Attention and Performance XII: The Psychology of Reading* (ed. Coltheart, M.) 559–589 (Erlbaum, London, 1987).
6. Taraban, R. & McClelland, J. R. Constituent attachment and thematic role assignment in sentence processing: Influence of context based expectations. *J. Mem. Lang.* **27**, 597–632 (1988).
7. Altman, G. T. M., Garnham, A. & Dennis, Y. Avoiding the garden-path: Eye movements in context. *J. Mem. Lang.* **31**, 685–712 (1992).
8. Cutler, A., Dahan, D. & van Donselaar, W. Prosody in the comprehension of spoken language: A literature review. *Lang. Speech* **40**, 141–201 (1997).
9. Blumstein, S. E. in *The Cognitive Neurosciences* (ed. Gazzaniga, M. S.) 915–929 (MIT Press, Cambridge, MA, 1995).
10. Hagoort, P. & Kutas, M. in *Handbook of Neuropsychology Vol.10* (eds. Boller, F. & Grafman, J.) 105–134 (Elsevier, Amsterdam, 1995).
11. Swaab, T. Y. *The Functional Locus of Comprehension Deficits in Aphasia: An Electrophysiological Approach* (Ponsen & Looijen, Wageningen, The Netherlands, 1996).
12. Osterhout, L. & Holcomb, P. J. Event-related brain potentials and syntactic anomaly: Evidence of anomaly detection during the perception of continuous speech. *Lang. Cogn. Processes* **8**, 413–437 (1993).
13. Osterhout, L., Holcomb, P. J. & Swinney, D. A. Brain potentials elicited by garden-path sentences. Evidence of the application of verb information during parsing. *J. Exp. Psychol. Learn. Mem. Cogn.* **20**, 786–806 (1994).
14. Osterhout, L. & Holcomb, P. J. in *Electrophysiology of Mind: Event-Related Potentials and Cognition* (eds. Rugg, M. D. & Coles, M. G. H.) 171–215 (Oxford Univ. Press, Oxford, 1995).
15. Friederici, A. D., Steinhauer, K., Mecklinger, A. & Meyer, M. Working memory constraints on syntactic ambiguity resolution as revealed by electrical brain responses. *Biol. Psychol.* **47**, 193–221 (1998).
16. Kutas, M. & Hillyard, S. A. Reading senseless sentences: Brain potentials reflect semantic incongruency. *Science* **207**, 203–205 (1980).
17. Holcomb, P. J. & Neville, H. J. Natural speech processing: An analysis using event-related brain potentials. *Psychobiology* **19**, 286–300 (1991).
18. Kutas, M. & van Petten, C. in *Handbook of Psycholinguistics* (ed. Gernsbacher, M. A.) 83–143 (Academic, San Diego, 1994).
19. Friederici, A. D., Steinhauer, K. & Frisch, S. Lexical integration: Sequential effects of syntactic and semantic information. *Mem. Cogn.* (in press).
20. Nespor, M. & Vogel, I. *Prosodic Phonology* (Foris, Dordrecht, 1986).
21. Selkirk, E. O. *Phonology and Syntax: The Relation between Sound and Structure* (MIT Press, Cambridge, 1984).
22. Halle, M. & Vergnaud, J. R. *An Essay on Stress* (MIT Press, Cambridge, 1987).
23. Gernsbacher, M. A. & Jescheniak, J. D. Cataphoric devices in spoken discourse. *Cogn. Psychol.* **29**, 24–58 (1995).
24. Rösler, F., Friederici, A. D., Pütz, P. & Hahne, A. Event-related brain potentials while encountering semantic and syntactic constraint violations. *J. Cogn. Neurosci.* **5**, 345–362 (1993).
25. Friedman, D., Simson, R., Ritter, W. & Papin, I. The late positive component (P300) and information processing in sentences. *Electroencephalogr. Clin. Neurophysiol.* **38**, 255–262 (1975).
26. Van Petten, C. & Kutas, M. Influences of semantic and syntactic context on open- and closed-class words. *Mem. Cogn.* **19**, 95–112 (1991).
27. Osterhout, L. & Hagoort, P. A superficial resemblance doen't necessarily mean that you're part of the family: Counterarguments to Coulson, King, and Kutas (1998) in the P600/SPS-P300 debate. *Lang. Cogn. Processes* (in press).
28. Friederici, A. D. The time course of syntactic activation during language processing: A model based on neuropsychological and neurophysiological data. *Brain Lang.* **50**, 259–281 (1995).
29. Hopf, J.-M., Bayer, J., Bader, M. & Meng, M. Event-related brain potentials and case information in syntactic ambiguities. *J. Cogn. Neurosci.* **10**, 264–280 (1998).
30. Bader, M. in *Reanalysis in Sentence Processing* (eds. Ferreira, F. & Fodor, J. D.) (Kluwer, Dordrecht, in press).
31. Beckman, M. E. The parsing of prosody. *Lang. Cogn. Processes* **11**, 17–67 (1996).
32. Fodor, J. D. Learning to parse? *J. Psycholinguistic Res.* **27**, 285–319 (1998).
33. Ross, E. D. in *Behavioral Neurology and Neuropsychology* (eds. Feinberg, T. E. & Farah, M. J.) 699–709 (McGraw-Hill, New York, 1997).
34. Oldfield, R. C. The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychology* **9**, 97–113 (1975).
35. Regan, D. *Human Brain Electrophysiology: Evoked Potentials and Evoked Magnetic Fields in Science and Medicine* (Elsevier, New York, 1989).
36. Huynh, H. & Feldt, L. A. Conditions under which mean square ratios in repeated measurement designs have exact F-distributions. *J. Am. Stat. Assoc.* **65**, 1582–1589 (1979).
37. Keppel, G. *Design and Analysis: A Researcher's Handbook* (Prentice-Hall, Englewood Cliffs, New Jersey, 1991).