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The neuronal dynamics of auditory language comprehension

(Akademievorlesung am 12. November 1998)

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Abstract

The temporal dynamics and the neurotopography of processes constituing auditory comprehension are described. The first part reviews brain imaging studies on phonological, semantic and syntactic processes. Then an event-related functional magnetresonance imaging study which systematically varies the presence/absence of semantic and syntactic information in the auditory input is presented. The data indicate that the left frontal operculum plays a particular part in syntactic processing during auditory comprehension. The second part focuses on neurophysiological studies providing data with a high temporal resolution. Experiments are presented which indicate that syntactic and semantic processes are independent during an early processing stage, but interact during a late processing stage. It appears that only prosodic information can affect syntactic parsing in an early stage of auditory comprehension. The impact of these data for psycholingistic models of auditory language processing is discussed.

1 Introduction

We know for more than a century that specific brain areas in the dominant left hemisphere support language processes. The early functional neuroanatomy was based on lesion studies. It is only in the last decade that functional neuroimaging methods such as the positron emission tomography (PET) and the functional magnetic resonance tomography (fMRT) providing information about the brain-

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[*] First appeared in: Y. Miyashita, A. P. Marantz and W. O'Neil (eds.), Image, Language, Brain, Cambridge, MA: The MIT Press, 1999. Used by permission of The MIT Press.

behavior relationship in the intact brain are available. Although quite essential for an adequate description of the biological basis of language the information concerning the "*where*" in the brain these processes take place cannot be sufficient, as language processes unfold in time. Therefore, it appears that an adequate description must include information about the *temporal* parameters of language processes. Ideally these two information types, namely the neurotopography and the temporal dynamics of the neuronal processes underlying language, will merge into a picture that not only identifies the specific components of the neuronal network responsible for language processes but, moreover, how and when these components interact in time.

The present chapter is an attempt to draw such a picture for the domain of language comprehension. First, I will briefly describe competing psycholinguistic models of language comprehension. Second, I will identify the particular brain regions involved in language comprehension as revealed by functional imaging and try to specify their specific function in this multifaceted process. Third, I will describe the temporal coordination of the brain activity as revealed by neurophysiological measures providing a high temporal resolution. It will become obvious that a fine grained temporal structure of syntactic and semantic processes underlies the human capacity to understand spoken language on-line.

Starting from psycholinguistic models of language comprehension it is clear that language processing requires the activation of phonological, syntactic and semantic information. All models agree that these different types of information are processed by different cognitive subcomponents during comprehension. They disagree, however, with respect to when these different types of information interact in time (see Frauenfelder & Tyler 1987). Two extreme positions can be identified. One position is marked by the so-called serial or syntax-first models which hold that the parser initially builds up a syntactic structure independent of lexical-semantic information (e.g. Frazier 1987a, b; Gorrell 1995). According to this type of models semantic aspects only come into play at a later stage, that is when thematic role assignment takes place. As long as the thematic representation is compatible with the initial syntactic structure built comprehension is directly achieved. If not, the parser has to pass through a revision stage adjusting the initial structure (e.g. Fodor & Inoue 1998). The alternative position is marked by the so-called interactive models. Although differing to some degree in their detail, interactive models hold that structural and semantic information interact during comprehension at any point in time (Marslen-Wilson & Tyler 1980; McClelland, St. John & Taraban 1989; Mac Donald, Just & Carpenter 1992; Bates, Devescovi, Hernandez & Pizzamiglio 1996). The issue of whether syntactic and semantic information interact immediately or late in the comprehension process still appears to be unresolved when consulting the behavioral literature. Additional evidence concerning the temporal structure of language processes and the possible interaction of different types of information, however, comes from electrophysiological studies using event-related brain potential (ERP) measures which allow to register the brain's activity as the input is encountered. These measures, in contrast to behavioral measures, do not register the result of a process, but are able to monitor the process as it develops in time. Thus ERPs provide the possibility to temporally segregate different subprocesses. Additional parameters of the ERP such as spatial distribution and polarity can help to distinguish different subprocesses.

But before turning to the temporal aspects of the brain's activity during language comprehension we will consider the particular brain structures involved. A spatial segregation of the different cognitive subprocesses constituing language comprehension will certainly add to the question of the functional independence of these subprocesses.

2 Functional neuroanatomy as revealed by brain imaging

The *phonological subsystem* of the auditory processing system has been localized in temporal as well as frontal brain regions by a number of PET and fMRI studies, mostly using single word presentation. It was shown that the superior temporal gyrus of the left and the right hemisphere is responsible for the perceptual analysis of speech signals. These brain regions are active when participants listen to language stimuli passively (Petersen, Fox, Posner, Mintum & Raichle 1988; Wise, Chollet, Hadar, Friston, Hoffner & Frackowiak 1991; Zatorre, Evans, Meyer & Gjedde 1992). This finding is supported by recent fMRI studies (Binder, Rao, Hammeke, Yetkin, Jesmanówicz, Bandettini, Wong, Estkowski, Goldstein, Haughton & Hyde 1994, for word listening; Schlosser, Aoyagi, Fulbright, Gore & McCarthy 1998, for sentence listening). The posterior region of the left temporal gyrus and the adjacent planum temporale is specifically involved in auditory language comprehension (Petersen, Fox, Posner, Mintum & Raichle 1989; Zatorre, Meyer, Gjedde & Evans 1996), as this region is not active when processing simple tones (Lauter, Herschovitch, Formby & Raichle 1985; Zatorre, Meyer, Gjedde & Evans 1992) or when discriminating tones (Démonet, Chollet, Ramsay, Cardebat, Nespoulous, Wise, Rascol & Frackowiak 1992; Démonet, Price, Wise & Frackowiak 1994).

In addition to these temporal areas, PET studies indicate an involvement of left inferior frontal regions in phonetic processing. Activation of Broca's area is reported to be most evident when the task requires a detailed analysis of phonetic units or phonetic sequences (Démonet et al. 1992; Zatorre et al. 1996). An inspection of the particular activation foci in the available studies seems to indicate that phonetic and phonological processing occurs in the superior-dorsal part of Brodmann area (BA44) adjacent to BA6, but not in the inferior-ventral part of BA44, classically called Broca's area. This observation suggests a functional distinction between the superior-dorsal and the inferior part of BA44. It was proposed that the superior-dorsal part is primarily involved in processing of phonetic sequences whereas the inferior part is primarily involved in processing syntactic sequences (Friederici 1998a; and see below).

The evaluation of the *semantic subsystem* has initially focused on visual word presentation. There are a number of studies investigating the different aspects of semantic processing. Early studies primarily used a combined comprehension-production task, i.e. the word generation task. In this task subjects are required to name a word which is semantically associated to a presented word (Petersen et al. 1989; Buckner, Petersen, Ojemann, Miezin, Squir & Raichle 1995; Wise et al. 1991). When using this paradigm without controlling for the production aspect activation was found in left BA45/46 and in BA44. When, however, extracting the particular activation responsible for the processing of semantic information during perception left BA47 is identified as the relevant area (Martin, Haxby, Lalonde, Wiggs & Ungerleider 1995; Martin, Wiggs, Ungerleider & Haxby 1996; Fiez 1997). This area seems to be active whenever strategic aspects of semantic processing are required. Processing semantic information while passively listening, in contrast, primarily activates the temporal region BA22/42, mostly bilaterally (Petersen et al. 1989; Petersen, Fox, Snyder & Raichle 1990; Frith, Friston, Liddle & Frackowiak 1991).

The *syntactic subsystem* so far has only been investigated in a few PET and fMRI studies, mostly on reading. In a PET study Stromswold et al. (Stromswold, Caplan, Alpert & Rauch 1996) registered participant's brain activation while reading English subject and object relative sentences. They reported a selective activation of the pars opercularis in the left third frontal convolution (BA44) as a function of syntactic complexity. This result was replicated in a more recent PET study using the same material (Caplan, Alpert & Waters 1998). In a fMRI study Just and colleagues (Just, Carpenter, Keller, Eddy & Thulborn 1996) also investigated the reading of English subject and object relative sentences. Similar to the PET studies they found maximal activation in the left third frontal convolution (BA44 and BA45), but additional activation in the left Wernicke's area as well as some activation in the homotopic areas in the right hemisphere. Activation in BA44 and BA45 was also found to be specially related to syntactic processing in reading complex Japanese sentences (Inui, Otsu, Tanaka, Okada, Nishizawa & Konishi 1998). In contrast, a PET study comparing the auditory processing of syntactically structured sentences containing pseudowords with unstructured lists of

pseudowords in French did not identify the Broca's area as being responsible for syntactic processes, but rather the left and right temporal pole (Mazoyer, Tzourio, Frak, Syrota, Murayama, Levrier, Salamon, Dehaene, Cohen & Mehler 1993).
In the following I will present a most recent fMRI study from our laboratory which aimed to identify the phonological, the semantic, and the syntactic subsystem by directly comparing the processing of different types of auditory language input within the same subjects. In contrast to the studies reported in which different sentence types were presented in homogeneous blocks, we used an event-related fMRI design in which different auditory stimulus types were presented in a pseudo randomized order.

The stimuli were of four different types: (1) normal sentences (hereafter called normal prose), (2) syntactically correct sentences with all function words and grammatical morphemes intact, but in which content words were replaced by pseudowords (hereafter called syntactic prose), (3) unstructured lists of content words (hereafter called real word lists), and (4) unstructured lists of phonologically legal pseudowords (hereafter called pseudoword lists).

(1) *The hungry cat hunts the quick mouse.**
(2) *The slonky clat wunts the reappy rosel.*
(3) *The cook storm cat velocity glory hole.*
(4) *The storf rool mong recelant laft apine.*

* Examples are English adaptations of German sentences and word lists applied in the present study.

These four conditions should allow the identification of the neuronal network involved in auditory language processing and the particular function of the areas identified.
Subjects were required to listen to these types of input and to judge whether the input had a syntactic structure and whether it contained real content words. Stimuli were presented in an unpredictable, i.e. pseudo randomized order. Eight scans were taken from each subject using a 3 Tesla fMRI.
The results from 18 subjects indicate that the patterns of activation vary as a function of the type of auditory language input. As expected, all auditory stimulus types caused activation in Heschl's gyri and the planum temporale bilaterally. By comparing the sentence versus the word list conditions we found particular regions to be stronger engaged in sentence processing (normal prose and syntactic prose) than in the processing of word lists (real words and pseudowords). These regions are the posterior portion of the superior temporal gyrus bilaterally and a cortex area at the mid-portion of the superior temporal sulcus in the left and right hemisphere, and furthermore, the banks of the left posterior ascending ramus of the

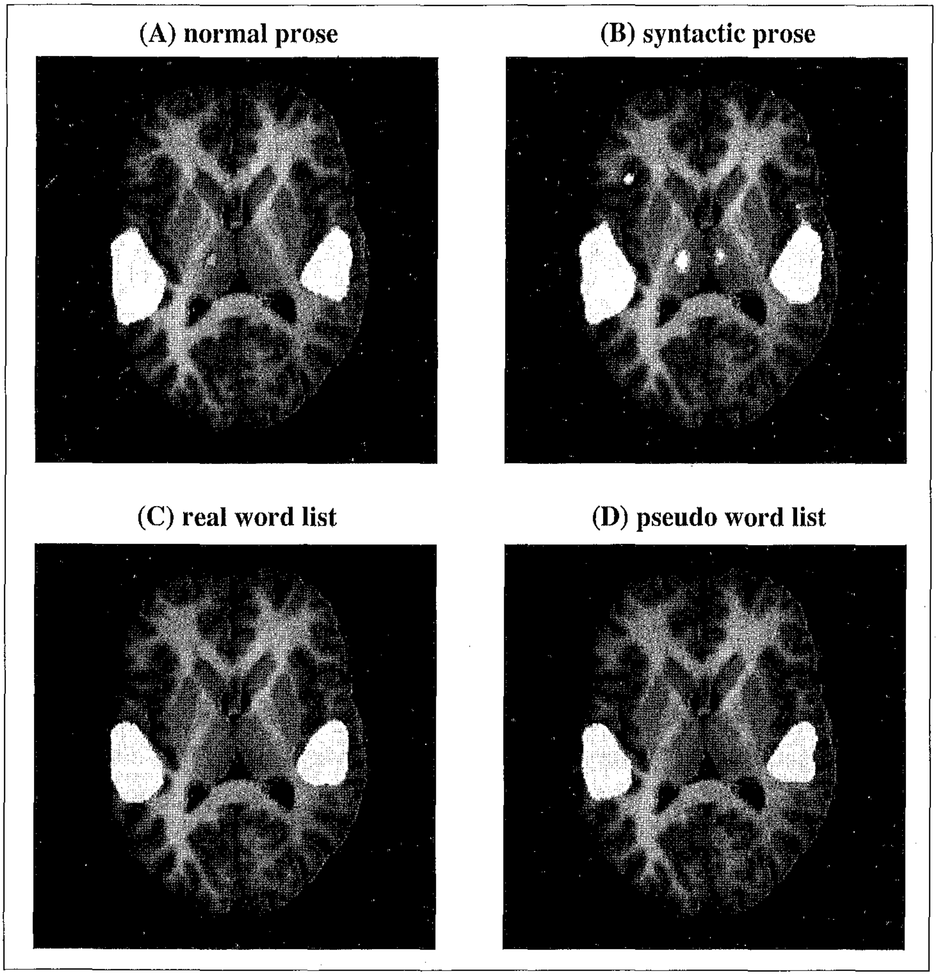

Figure 1
Significant clusters of activation for four different auditory stimulus conditions in the left hemisphere as indicated by fMRI illustrated in a sagittal view.

Sylvian fissure (planum parietale). In addition, a considerable increase in blood flow occurred in the thalamus bilaterally, in the two prose conditions, but not in the word list conditions. Interestingly, normal prose showed generally less activation than syntactic prose. Processing of the latter was correlated with additional activation in the deep left frontal operculum, in the cortex lining the junction of the inferior precentral sulcus and the inferior frontal sulcus bilaterally as well as in the ascending branch of the left intraparietal sulcus unilaterally.

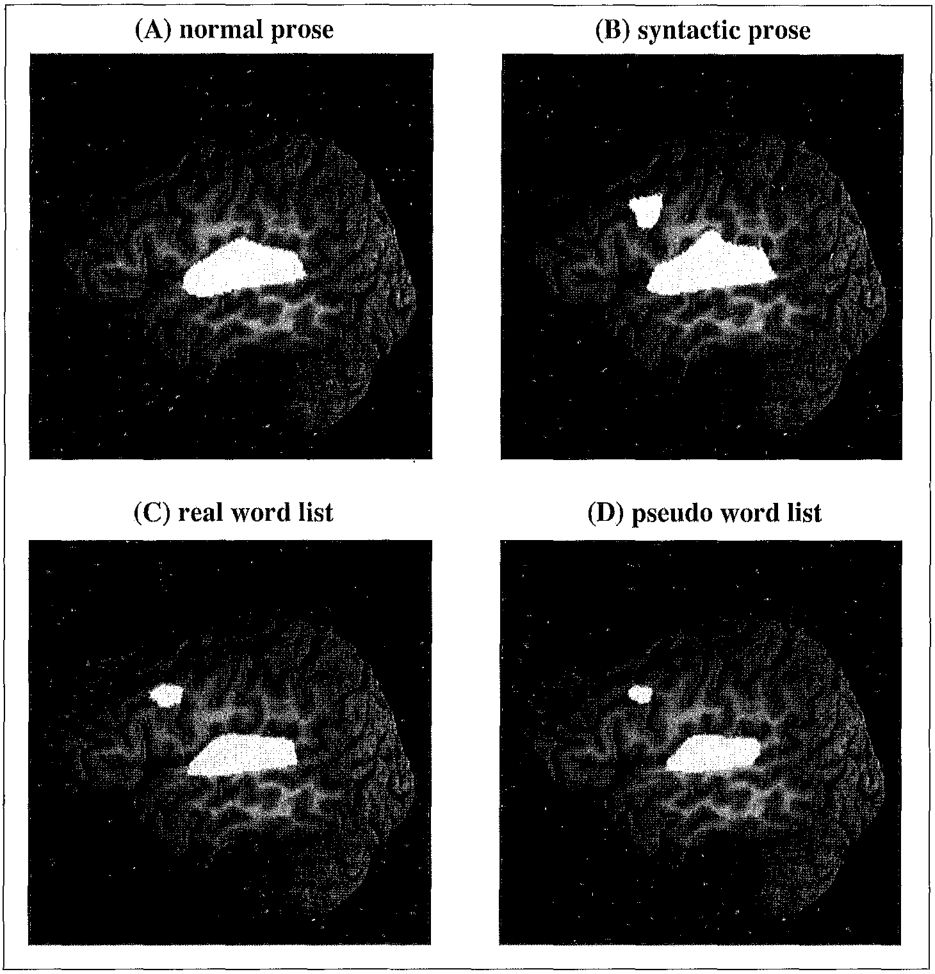

Figure 2
Significant clusters of activation for four different auditory stimulus conditions bilaterally as indicated by fMRI illustrated in the horizontal view.

For word lists, independent of whether they consisted of pseudowords or real words, the activation in the left as well as in the right superior temporal gyrus was reduced compared to the two prose conditions. Both types of word lists activate the cortex lining the junction of the left inferior precentral sulcus and the inferior frontal sulcus. The two types of word lists, however, could be differentiated from each other by an activation in the homotopic cortex of the right hemisphere which was observed for real words, but not for pseudowords.

Thus the cerebral network subserving auditory sentence processing includes the left temporal and inferior frontal cortex as well as its right hemisphere homotopic regions. Systematic comparisons between the different conditions allow a functional specification of particular brain areas associated with language comprehension. The processing of *phonological information* is correlated with significant activation in the primary auditory cortices and in the posterior segment of the superior temporal gyrus bilaterally including the planum temporale. In addition, a small part of the cortex at the junction of the inferior precentral sulcus and the inferior frontal sulcus in the left hemisphere seems to be involved in phonological processing. Processing of *semantic information* in this study was correlated with an additional small activation focus in the right superior-dorsal part of Broca's area. Processing of *syntactic information* during auditory sentences comprehension was reflected by a considerable increase of the hemodynamic response in the superior temporal gyrus bilaterally extending to its mid-portion, and further with a specific activation in the deep portion of the left frontal operculum, nearby the pars triangularis in the Broca's area[1]. Interestingly, the left frontal operculum was only significantly activated during syntactic prose, but not during normal prose. This might suggest that processing of normal speech occurs automatically not requiring the additional cerebral resources of the left frontal operculum. Additional resources associated with activation in the left inferior frontal region, however, may be required when complex sentences are to be read (Just et al. 1996; Stromswold et al. 1996; Caplan et al. 1998), or when syntactic processing is required in the presence of pseudowords.

3 Functional neurochronometry as revealed by electrophysiology

Research concerning the electrophysiological markers of language processing provides quite a number of studies looking at different aspects of language processing. Auditory perception and *phonological* processes have been investigated using electroencephalographic (EEG) and magnetoencephalographic (MEG) measures. The early acoustic processes are reflected by the N100/P200 complex in the event-related brain potential (ERP). These components vary as a function of stimulus intensity, presentation rate and attention (Näätänen & Picton 1987). Phonological processes as investigated by EEG and MEG experiments at the consonant-vowel level indicate that primary auditory processes are supported by the posterior part of the primary auditory cortices whereas language specific processes also involve

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[1] Note that prosodic information supporting bracketing of the language input is also available in the stimulus. Experiments to disentangle prosodic and syntactic parsing in the fMRI are currently carried out.

the superior part of the left temporal lobe. This conclusion is based on the finding that the M100, the magnetic counterpart of the electric N100, in response to passive listening is localized in these areas (Kuriki & Murase 1989; Poeppel, Yellin, Phillips, Roberts, Rowley, Wexler & Marantz 1996). When phoneme discrimination is required there is an asymmetrical activation with a dominance in the left hemisphere (Poeppel et al. 1996). For further details see Marantz and Poeppel (Marantz & Poeppel, 1999).

The early ERP research on word and sentence processing generally used a visual presentation mode. In all sentence processing studies sentences were presented visually without exception in word-by-word manner with pauses up to 800 ms between each word. The seminal study by Kutas and Hillyard (1980, 1983) had identified a specific ERP component for the processing of *semantic* information. This component is a negativity about 400 ms post onset of a word whose semantic integration into the prior context is either impossible or difficult. With reference to its polarity and temporal characteristics this component is called N400. The component is usually broadly distributed over the posterior part of both hemispheres slightly lateralized to the right. A review of all the studies of the N400 is beyond the scope of this chapter (for a review see Van Petten 1995). Here it may suffice to mention that the N400 was observed in a number of different languages, it was found for semantically anomalous words in word context as well as in sentence context, moreover, it was identified in the visual as well as in the auditory domain. Functionally the N400 is taken as a general marker for semantic processes (Kutas & Hillyard 1980, 1983). More recently, its function has been specified as reflecting lexical-semantic integration in particular, rather than processes of lexical access or semantic processes in general (Chwilla, Brown & Hagoort 1995).

With respect to *syntactic* processes two ERP components have been identified: a left anterior negativity and a late positivity. These two components are taken to reflect different stages of syntactic processing, an early phase of initial structure building and a later phase of secondary processes including reanalysis and repair (Friederici 1995). An early left anterior negativity (ELAN) between 100 and 200 ms was observed in response to phrase structure violations realized as word category errors (Neville, Nicol, Barss, Forster & Garrett 1991; Friederici, Pfeifer & Hahne 1993). A left anterior negativity (LAN) between 300 and 500 ms has been registered in response to morphosyntactic violations (Coulson, King & Kutas 1998; Gunter, Stowe & Mulder 1997; Penke, Weyerts, Gross, Zander, Münte, & Clahsen 1997; Münte, Matzke & Johannes 1997), as well as in response to verb argument violations (Rösler, Friederici, Pütz & Hahne 1993). While these negativities are only evoked by outright violations a centro-parietal positivity around 600 ms, labeled P600, is observed both with the processing of garden-path sentences

(Osterhout & Holcomb 1992, 1993; Friederici, Steinhauer, Mecklinger & Meyer 1998) and with outright syntactic violations (following the left anterior negativity) (Gunter et al. 1997; Coulson et al. 1998; Hahne & Friederici 1999a).

The combined language related ERP findings have lead to the proposal that there are three processing stages during language comprehension (Friederici 1995): (1) an early stage of first-pass parsing during which the initial structure is build on the basis of categorical information (see also Frazier 1987a, b). This first-pass parsing stage is reflected by the ELAN (100–200 ms) observable for word category violations. (2) During the second stage (300–500 ms) lexical information is processed: lexical integration difficulties are reflected in the N400. Difficulties of this kind are observed with violations concerning the semantic relation between lexical elements i.e. between nouns, or between a particular verb and a noun (e.g., selectional restriction violation). Violations concerning the syntactic agreement relation between lexical elements (e.g., case violation and agreement violation) indicated by semantically uninterpretable morphology (Chomsky 1995), in contrast, appear to be reflected in a LAN.[2] (3) The third stage is correlated with the late positivity. This P600 component appears to reflect a stage of secondary processes during which garden-path sentences are revised and incorrect sentences are repaired.
The discussion concerning the particular functional identity of the P600 is still ongoing. While some authors view the P600, also called Syntactic Positive Shift (Hagoort et al. 1993), as the primary reflection of syntactic processes (Osterhout & Holcomb 1992; Hagoort, Brown & Groothusen 1993), others take it to reflect secondary syntactic processes (Friederici et al. 1993; Friederici 1995; Münte et al. 1997), whereas some take the P600 as an index for syntactic integration difficulty in general (Kaan, Harris, Gibson & Holcomb 1998). The latter notion implies not that the difficulty may not be determined by purely structural factors, but possibly also be mediated by discourse and thematic factors (Gibson 1998).

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[2] This temporal hierarchy in the availability of categorical and semantic information may dependent on when during the input the different types of information become available. For example in morphologically rich languages, word category may be marked by the suffix and is thus only available late during auditory language perception. The results by Friederici et al. (1996) indicate that the 'early left anterior negativity' is registered later when measured from the word onset for those words which mark their word category information in a suffix. When, however, measured from the word category decision point the latency of the left anterior negativity again falls in the 'early' time window.

3.1 When syntax meets semantics[3]

All ERP studies evaluated the interaction of syntactic information and semantic information the two factors. Thus, in each of the studies there were four conditions: a correct condition, a condition in which the critical word violated the context with respect to either semantic aspects, syntactic aspects, or both. While semantic violations were either realized as selectional restriction violations or as a variation in semantic expectancy (cloze probability) in these studies, they differed systematically in how the syntactic violation was realized. Two visual studies realized the syntactic violation as a morpho-syntactic error, whereas one visual and one auditory study realized the syntactic violation as a word category error violating the phrase structure.

The two studies which investigate the interaction of a morpho-syntactic violation (gender agreement) and a semantic variable (Gunter, Friederici & Schriefers 1998; Hagoort & Brown 1997) come to different conclusions. Hagoort and Brown (1997) found an additive effect for the N400 in the critical double violation condition. The results of Gunter et al. (1998), in contrast, show an N400 as a function of the (semantic) cloze probability independent of the gender agreement violation, and a left anterior negativity between 300 and 500 ms as a function of gender agreement violation independent of the semantic variable. A P600 varied as a function of both the gender agreement violation and the cloze probability. The findings from the latter study seem to indicate that morpho-syntactic and semantic aspects are processed independently and in parallel around 400 ms, and that the two types of information do interact only during a later stage.

The following two studies investigated the interaction between a phrase structure violation and a semantic violation (Friederici, Steinhauer & Frisch 1999; Hahne & Friederici 1998). Here only the latter study will be presented as the former was conducted in the visual domain. Details of the former are available in Friederici et al. (1999).

The auditory experiment (Hahne & Friederici 1998) comprised four conditions: (5) correct sentences, (6) sentences containing a selectional restriction violation, (7) sentences containing a phrase structure violation and (8) sentences containing a double violation.

(5) Das Baby wurde gefüttert.
The baby was fed.

(6) * Das Lineal wurde gefüttert.
The ruler was fed.

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[3] Note, that I borrowed the title of this section from a paper by Gunter et al. (1997).

(7) * Die Gans wurde im <u>gefüttert.</u>[4]
The goose was in the fed.

(8) * Die Burg wurde im <u>gefüttert.</u>
The castle was in the fed.

Subjects listened to sentences of these types in pseudo randomized order. After each sentence they were required to indicate the sentence's grammaticality with respect to syntactic and meaning aspects. ERPs were recorded from 19 electrodes.

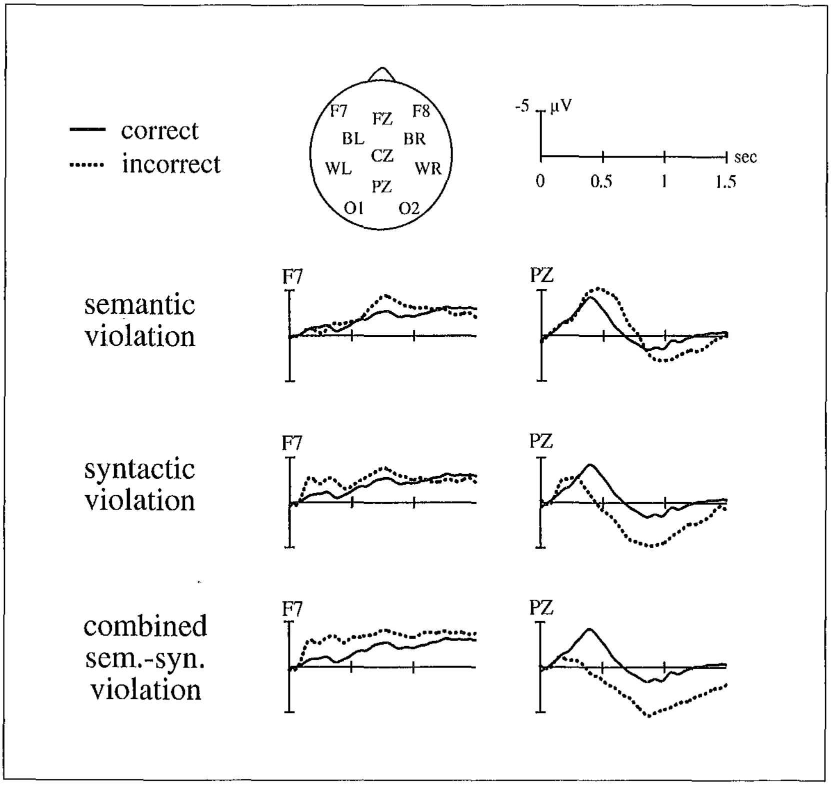

Figure 3
Average of event-related brain potentials for the semantically incorrect condition, the syntactically incorrect condition, and the combined violation condition plotted against the correct condition. Vertical line indicates onset of the critical word. Negative voltage is plotted up.

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[4] The phrase structure violation is due to the fact that the word following the preposition is a verb since the preposition (concatenated with the article: in + dem becomes im) obligatorily requires a noun before the sentence final verb.

The ERP patterns for each violation condition compared to the correct condition were as follows. For the semantic condition we found the expected N400 component. For the syntactic condition we observed a biphasic early negativity – late positivity pattern. For the double violation condition we found an early left anterior negativity and a P600, but no N400. These findings seem to suggest that a phrase structure violation detected early, as indicated by the early left anterior negativity, can block lexical integration processes usually reflected by the N400. From these data we can conclude that phrase structure building processes, based on categorical information, can precede lexical-semantic integration processes as proposed by syntax-first models.

With respect to the psycholinguistic discussion of whether semantic and syntactic information interact, the present data indicate that these two information types interact during a late stage in the comprehension process as reflected in the P600. In the early stage there appear to be two phases, a very early phase during which only categorical information is processed (100–200 ms) and a later phase during which lexical-semantic and morphosyntactic information are active. Gender information and meaning information seem to be processed in parallel as indicated by the independence of the LAN effect from the semantic variable and the independence of the N400 effect (Gunter et al. 1998). However, it appears that categorical information when being available early from morphosyntactic markers can influence meaning processes, though not vice versa. The available ERP data show that lexical-semantic integration may be blocked in case it is not licensed by the phrase structure rules (Friederici et al. 1999; Hahne & Friederici 1998, 1999b). This latter finding supports serial syntax-first models which restrict the first-pass parse to phrase structure building on the basis of categorical information. Other types of syntactic information are processed in parallel but independent from meaning providing evidence for parallel models. The interaction of semantic and syntactic information during a late processing stage may be responsible for behavioral findings supporting highly interactive models. Thus these data demonstrate that an adequate model of language comprehension may gain from the neurochronometry of the processes involved.

3.2 When syntax meets prosody

Most language comprehension models do not consider the auditory processing of language in particular. However, reaction time studies suggest that prosodic information available in the auditory input can influence syntactic processes quite substantially (Marslen-Wilson, Tyler, Warren, Grenier & Lee 1992; Warren, Grabe & Nolan 1995). The question that arises is at what stage does prosodic information come into play. As prosodic information is available early during auditory language comprehension it may well be that it affects syntactic processes already at its early stage.

We investigated this question in a study that used sentences with phrase structure violations realized as word category errors, similar to the previous study, and crossed this violation type with an inadequate intonational pattern, i.e. stress at the word preceding the word category error (Jescheniak, Hahne & Friederici 1998).

Crossing these variables resulted in four different sentence types: sentences that were syntactically correct and prosodically adequate as in (5), sentences that were syntactically incorrect, but prosodically adequate as in (7), sentences that were syntactically correct and with an inadequately stressed preposition as in (11) and sentences with a double violation (12) containing a phrase structure error at the word *fed* which was preceded by in inappropriately stressed preposition (indicated by capital letters).

(11) * Die Gans wurde IM Stall gefüttert.
The goose was IN THE barn fed.

(12) * Die Gans wurde IM gefüttert.
The goose was IN THE fed.

Interestingly, for sentences like (11) no ELAN was observed, which was, however, found for the prosodically adequate counterpart. This seems to suggest that prosodic information such as word stress can influence first-pass parsing processes, at least those involved in the detection categorical violations.

In a recent ERP experiment in which we presented correct, but temporally structurally ambiguous sentences we were able to show the early influence of prosodic information on normal phrase structure building processes (Steinhauer, Alter & Friederici 1999).
The German sentences (13) and (14) are structurally ambiguous up to the second verb which disambiguates the structure indicating whether *Anna* is the object of the first verb (13) or the second verb (14).

(13) [Peter verspricht Anna zu arbeiten] $_{IP1}$ [und ...]
Peter promises Anna to work and ...

(14) [Peter verspricht] $_{IP1}$ [Anna zu entlasten] $_{IP2}$ [und ...]
Peter promises to support Anna and ...

When looking at the bracketing of the intonational phrases (IPs) the prosodic differences between these two sentence types become obvious: there is an additional intonational phrase boundary in (14) prosodically realized by the insertion of a pause after the first verb.

In our experiment a similar pause was inserted in the original sentence type (13), in order to test whether this inadequate prosodic information misguides the early syntactic parse. If so, we expect an ERP effect at the disambiguating second verb in sentence type (13').

(13') *[Peter verspricht] $_{IP1}$ [Anna zu arbeiten] $_{IP2}$ [und ...] $_{IP3}$
Peter promises Anna to work and ...

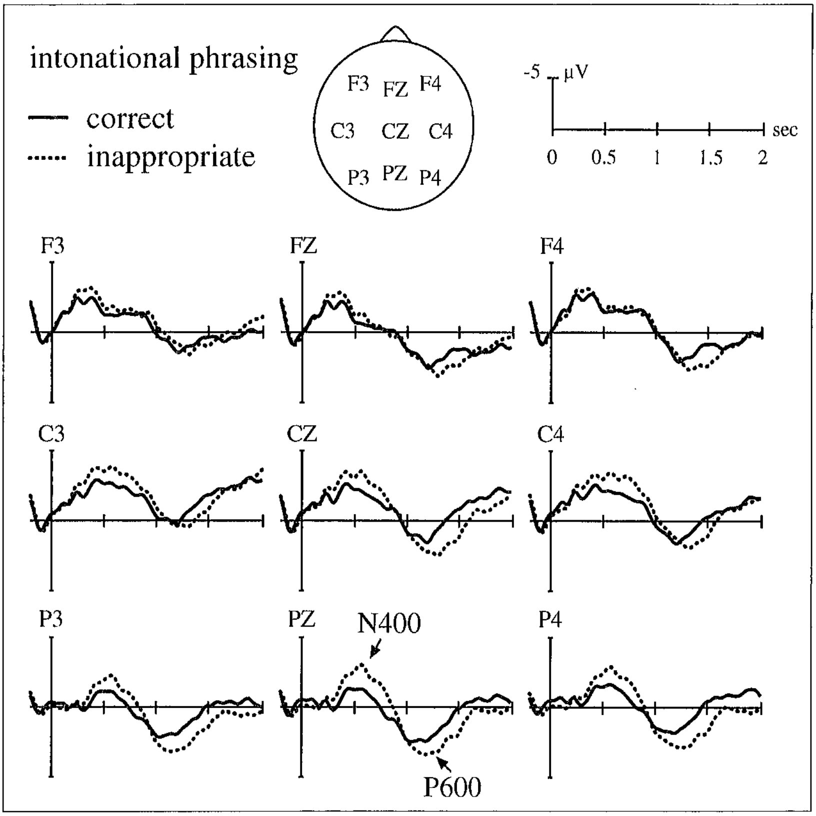

Figure 4
Average of event-related brain potentials for the critical (second) verb in sentences with appropriate intonational phrasing and in sentences with inappropriate intonational phrasing. Vertical line indicates the onset of the critical verb. Negative voltage is plotted up.

Comparing the verb in the appropriately paused sentence (14) and in the sentence (13') with an inappropriately inserted pause after the first verb we observed an N400 effect followed by a P600. This pattern indicates that subjects indeed misparsed the sentence (13') with the inappropriate prosodic condition expecting a transitive verb. Thus, when encountering the intransitive verb the system first signals the unexpected verb (N400) and than reanalyzes the initial parse (P600). This finding clearly indicates that prosodic information can influence the initial syntactic parse. Psycholinguistic models dealing with auditory language comprehension will have to take this into consideration.

3.3 A tentative model

A tentative model of the neuronal dynamics of auditory language comprehension can be sketched as follows.[5] When processing the speech sound the system already receives early structural information, namely by prosody. The bracketing provided by prosodic information does not entirely map onto syntactic bracketing, but the overlap is large and recent ERP data show that the prosodic structure is dominant during the initial parsing stage. The tide link between prosodic and syntactic structure allows a very fast initial parse (Steinhauer et al. 1999; Jescheniak et al. 1998). Word category information is soon available to build the local phrase structure (Friederici et al. 1993; Hahne & Friederici 1999a, b). This early syntactic process is independent of lexical-semantic information (Hahne & Friederici 1998). Lexical-semantic information only comes into play when thematic roles are assigned. If initial syntactic structure and thematic structure map well, comprehension has taken place adequately, if not, the system has to revise the former structures either by a syntactically licensed reanalysis (Friederici 1998b) or a thematically guided repair process (Gunter et al. 1998).

4 A final note:
How can the neuronal activity and the hemodynamic response meet?

The goal of the neurocognitive approach to language is to ultimately bring together information concerning the neuronal network supporting the human ability to comprehend (and produce) language and information about how the different subcomponents of the network are temporally organized. So far the relation between

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[5] Here I will refer to the data presented in this chapter. Reference to work from other laboratories was provided in previous sections.

the neuronal activity measured by EEG or MEG and the hemodynamic response as registered by PET or fMRI is not well understood. Also, the direct coupling between the particular neurophysiological and hemodynamic data is not obvious. For example, the relation between the N400 and those brain areas that hold responsible for semantic processes is far from being clear. Using intracranial electrophysiological measures the neuronal generators of the N400 have been localized within the anterior medial part of the temporal lobe bilaterally (Nobre, Allison & McCarthy 1994). Although, the scalp distribution of the N400 is compatible with fMRI studies reporting bilateral activation in the superior temporal gyrus and the superior temporal sulcus for semantic processing during listening (e.g. Démonet et al. 1992; Binder et al. 1994), the relation between the activation in the left frontal gyrus registered by PET and fMRI and the distribution of the N400 component in the ERP is still unclear. One possible explanation for the latter, less obvious relation may be that those processes correlated with the frontal activation are not part of those processes reflected by the N400. This is not unlikely as the activation in the left frontal gyrus has been correlated with strategic semantic processes in particular (e.g. Fiez 1997).

When trying to combine the brain imaging data and the electrophysiological findings with respect to syntactic processes we can only speculate that the processes concerning the phrase structure rules reflected in the early left anterior negativity are supported by the brain area identified as the left frontal operculum and possibly the mid-portion of the superior temporal gyrus in the fMRI study. Future research will have to resolve the direct relation between the hemodynamic and the neurophysiological response in general, and for language processes in particular.

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References

Bates, E., Devescovi, A., Hernandez, A. & L. Pizzamiglio: Gender priming in Italian. In: Perception and Psychophysics, 58 (1996) 7, pp. 992-1004.

Binder, J. R., Rao, S. M., Hammeke, T. A., Yetkin, F. Z., Jesmanówicz, A., Bandettini, P. A., Wong, E. C., Estkowski, L. D., Goldstein, M. D., Haughton, V. M. & J. S. Hyde: Functional magnetic resonance imaging of human auditory cortex. In: Annals of Neurology, 35 (1994), pp. 662-672.

Buckner, R. L., Petersen, S. E., Ojemann, J. G., Miezin, F. M., Squire, L. R. & M. E. Raichle: Functional anatomic studies of explicit and implicit memory retrieval tasks. In: Journal of Neurosciences, 15 (1995), pp. 12-29.

Caplan, D., Alpert, N. & G. Waters: Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. In: Journal of Cognitive Neuroscience, 10 (1998) 4, pp. 541-552.

Chomsky, N.: The Minimalist Program, Cambridge, MA: MIT Press, 1995.

Chwilla, D. J., Brown, C. M. & P. Hagoort: The N400 as a function of the level of processing. In: Psychophysiology, 32 (1995), pp. 274-285.

Coulson, S., King, J. W. & M. Kutas: Expect the unexpect: Event-related brain response to morphosyntactic violations. In: Language and Cognitive Processes, 13 (1998), pp. 21-58.

Démonet, J.-F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.-L., Wise, R., Rascol, A. & R. Frackowiak: The anatomy of phonological and semantic processing in normal subjects. In: Brain, 115 (1992), pp. 1753-1768.

Démonet, J.-F., Price, C., Wise, R. & R. S. J. Frackowiak: A PET study of cognitive strategies in normal subjects during language tasks. Influence of phonetic ambiguity and sequence processing on phoneme monitoring. In: Brain, 117 (1994), pp. 671-682.

Fiez, J. A.: Phonology, semantics, and the role of the left inferior prefrontal cortex. In: Human Brain Mapping, 5 (1997), pp. 79-83.

Fodor, J. D. & A. Inoue: Attach anyway. In: Ferreira, F. & J. D. Fodor (eds.), Reanalysis in Sentence Processing, Dordrecht: Kluwer Academic Publishers, 1998.

Frauenfelder, U. H. & L. K. Tyler: The process of spoken word recognition: An introduction. In: Cognition, 25 (1987), pp. 1-20.

Frazier, L.: Sentence processing: A tutorial review. In: Coltheart, M. (ed.), Attention and performance XII, Hillsdale, NJ: Erlbaum, 1987a, pp. 559-586.

Frazier, L.: Theories of sentence processing. In: Garfield, J. (ed.), Modularity in knowledge representation and natural-language processing, Cambridge, MA: MIT Press, 1987b, pp. 291-307.

Friederici, A. D.: The time course of syntactic activation during language processing: A model based on neuropsychological and neurophysiological data. In: Brain and Language, 50 (1995), pp. 259-281.

Friederici, A. D.: The neurobiology of language comprehension. In: Friederici, A. D. (ed.), Language Comprehension: A biological Approach, Berlin/Heidelberg/New York: Springer, 1998a, pp. 263-301.

Friederici, A. D.: Diagnosis and reanalysis: Two processing steps the brain may differentiate. In: Fodor, J. & F. Ferreira (eds.), Reanalysis in sentence processing, Dordrecht: Kluwer, 1998b, pp. 177-200.

Friederici, A. D., Hahne, A. & A. Mecklinger: The temporal structure of syntactic parsing: Early and late event-related brain potential effects elicited by syntactic anomalies. In: Journal of Experimental Psychology: Learning, Memory, and Cognition, 22 (1996), pp. 1219-1248.

Friederici, A. D., Pfeifer, E. & A. Hahne: Event-related brain potentials during natural speech processing: Effects of semantic, morphological and syntactic violations. In: Cognitive Brain Research, 1 (1993), pp. 183-192.

Friederici, A. D., Steinhauer, K. & S. Frisch: Lexical integration: Sequential effects of syntactic and semantic information. In: Memory and Cognition, 27 (1999), pp. 438-453.

Friederici, A. D., Steinhauer, K., Mecklinger, A. & M. Meyer: Working memory constraints on syntactic ambiguity resolution as revealed by electrical brain responses. In: Biological Psychology, 47 (1998), pp. 193-221.

Frisch, S. & A. D. Friederici: Verb-argument structure processing: The influence of verb-specific and argument-specific constraints. Paper presented at 'The 11th Annual CUNY Conference on Human Sentence Processing', New Brunswick, NJ: Rutgers University, 1998.

Frith, C. D., Friston, K. J., Liddle, P. F. & R. S. J. Frackowiak: A PET study of word finding. In: Neuropsychologia, 29 (1991), pp. 1137-1148.

Gibson, E.: Linguistic complexity: Locality of syntactic dependencies. In: Cognition, 68 (1998), pp. 1-76.

Gorrell, P.: Syntax and Parsing, Cambridge, UK: Cambridge University Press (1995).

Gunter, T. C., Friederici, A. D. & H. Schriefers: Gender violations, semantic expectancy and ERPs. Poster presented at the 12th International conference on Event-Related potentials at the Brain, Boston, USA, 1998.

Gunter, T. C., Stowe, L. A. & G. Mulder: When syntax meets semantics. In: Psychophysiology, 34 (1997), pp. 660-676.

Hagoort, P. & C. Brown: When syntax and semantics meet. Poster presented at the fourth annual meeting of the Cognitive Neuroscience Society, Boston, USA, 1997.

Hagoort, P., Brown, C. & J. Groothusen: The syntactic positive shift as an ERP-measure of syntactic processing. In: Language and Cognitive Processes, 8 (1993), pp. 439-483.

Hahne, A. & A. D. Friederici: ERP-evidence for autonomous first-pass parsing processes in auditory language comprehension. In: Journal of Cognitive Neuroscience, Suppl., (1998), p. 125.

Hahne, A. & A. D. Friederici: Electrophysiological evidence for two steps in syntactic analysis: Early automatic and late controlled processes. In: Journal of Cognitive Neuroscience, 11 (1999a), pp. 193-204.

Hahne, A. & A. D. Friederici: Rule-application during language comprehension in the adult and the child. In: Friederici, A. D. & R. Menzel (eds.), Learning: Rule Extraction and Representation, Berlin: de Gruyter, 1999b, pp. 71-88.

Inui, T., Otsu, Y., Tanaka, S., Okada, T., Nishizawa, S. & J. Konishi: A functional MRI analysis of comprehension processes of Japanese sentences. In: NeuroReport, 9 (1998) 14, pp. 3325-3328.

Jescheniak, J. D., Hahne, A. & A. D. Friederici: Brain activity patterns suggest prosodic influences on syntactic parsing in the comprehension of spoken sentences. In: Music Perception, 16 (1998), pp. 55-62.

Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F. & K. R. Thulborn: Brain activation modulated by sentence comprehension. In: Science, 274 (1996), pp. 114-116.

Kaan, E., Harris, A., Gibson, E. & P. Holcomb: The P600 as an index of syntactic integration difficulty. Paper presented at the AMLaP-98 Architectures and Mechanisms for Language Processing, Freiburg, Germany, 1998.

Kuriki, S. & M. Murase: Neuromagnetic study of the auditory responses in right and left hemispheres of the human brain evoked by pure tones and speech sounds. In: Experimental Brain Research, 77 (1989), pp. 127-134.

Kutas, M. & S. A. Hillyard: Reading senseless sentences: Brain potentials reflect semantic incongruity. In: Science, 207 (1980), pp. 203-205.

Kutas, M. & S. A. Hillyard: Event-related brain potentials to grammatical errors and semantic anomalies. In: Memory and Cognition, 11 (1983), pp. 539-550.

Lauter, J. L., Herschovitch, P., Formby, C. & M. E. Raichle: Tonotopic organization in the human auditory cortex revealed by position emission tonography. In: Hearing Research, 20 (1985), pp. 199-205.

MacDonald, M. A., Just, M. A. & P. A. Carpenter: Working memory constraints on the processing of syntactic ambiguity resolution. In: Cognitive Psychology, 24 (1992), pp. 56-98.

Marantz, A. P. & D. Poeppel: Cognitive neuroscience of speech processing. In: Miyashita, Y., Marantz, A. P. & W. O'Neil (eds.), Image, Language, Brain, 1999.

Marslen-Wilson, W. D. & L. K. Tyler: The temporal structure of spoken language understanding. In: Cognition, 8 (1980), pp. 1-71.

Marslen-Wilson, W., Tyler, L. K., Warren, P., Grenier, P. & C. S. Lee: Prosodic effects in minimal attachment. In: The Quarterly Journal of Experimental Psychology, 45A (1992), pp. 73-87.

Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L. & L. G. Ungerleider: Discrete cortical regions associated with knowledge of colour and knowledge of action. In: Science, 270 (1995), pp. 102-105.

Martin, A., Wiggs, C. L., Ungerleider, L. G. & J. V. Haxby: Neural correlates of category-specific knowledge. In: Nature, 379 (1996), pp. 649-652.

Mazoyer, B. M., Tzourio, N., Frak, V., Syrota, A., Murayama, N., Levrier, O., Salamon, G., Dehaene, S., Cohen, L. & J. Mehler: The cortical representation of speech. In: Journal of Cognitive Neuroscience, 5 (1993), pp. 467-479.

McClelland, J. L., St. John, M. & R. Taraban: Sentence comprehension: A parallel distributed processing approach. In: Language and Cognitive Processes, 4 (1989), pp. 287-335.

Münte, T. F., Matzke, M. & S. Johannes: Brain activity associated with syntactic incongruencies in words and pseudo-words. In: Journal of Cognitive Neuroscience, 9 (1997), pp. 318-329.

Näätänen, R. & T. Picton: The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. In: Psychophysiology, 24 (1987), pp. 375-425.

Neville, H. J., Nicol, J., Barss, A., Forster, K. & M. Garrett: Syntactically based sentence processing classes: Evidence from event-related brain potentials. In: Journal of Cognitive Neuroscience, 3 (1991), pp. 155-170.

Nobre, A. C., Allison, T. & G. McCarthy: Word recognition in the human inferior temporal lobe. In: Nature, 372 (1994), pp. 260-263.

Osterhout, L. & P. J. Holcomb: Event-related brain potentials elicited by syntactic anomaly. In: Journal of Memory and Language, 3 (1992) 1, pp. 785-804.

Osterhout, L. & P. J. Holcomb: Event-related potentials and syntactic anomaly: Evidence of anomaly detection during the perception of continuous speech. In: Language and Cognitive Processes, 8 (1993), pp. 413-437.

Penke, M., Weyerts, H., Gross, M., Zander, E., Münte, T. F. & A. Clahsen: How the brain processes complex words: An ERP-study of German verb inflections. In: Cognitive Brain Research, 6 (1997), pp. 37-52.

Petersen, S. E., Fox, P. T., Posner, M. I., Mintum, M. & M. E. Raichle: Positron emission tomographic studies of the processing of single words. In: Journal of Cognitive Neuroscience, 1 (1989), pp. 153-170.

Petersen, S. E., Fox, P. T., Posner, M. I., Mintum, M. A. & M. E. Raichle: Positron emission tomographic studies of the cortical anomaly of single-word processing. In: Nature, 331 (1988), pp. 585-589.

Petersen, S. E., Fox, P. T., Snyder, A. Z. & M. E. Raichle: Activation of extrastriate and frontal cortical areas by visual words and work-like stimuli. In: Science, 249 (1990), pp. 1041-1044.

Poeppel, D., Yellin, E., Phillips, C., Roberts, T. P. L., Rowley, H. A., Wexler, K. & A. Marantz: Task-induced asymmetry of the auditory evoked M100 neuromagnetic field elicited by speech sounds. In: Cognitive Brain Research, 4 (1996), pp. 231-242.

Rösler, F., Friederici, A. D., Pütz, P. & A. Hahne: Event-related brain potentials while encountering semantic and syntactic constraint violations. In: Journal of Cognitive Neuroscience, 5 (1993), pp. 345-362.

Schlosser, M. J., Aoyagi, N., Fulbright, R. K., Gore, J. C. & G. McCarthy: Functional MRI studies of auditory comprehension. In: Human Brain Mapping, 6 (1998), pp. 1-13.

Steinhauer, K., Alter, K. & A. D. Friederici: Brain potentials indicates immediate use of prosodic cues in natural speech processing. In: Nature Neuroscience, 2 (1999), pp. 191-196.

Stromswold, K., Caplan, D., Alpert, N. & S. Rauch: Localization of syntactic comprehension by positron emission tomography. In: Brain and Language, 52 (1996), pp. 452-473.

Van Petten, C.: Words and Sentences: Event-related brain potential measures. In: Psychophysiology, 32 (1995), pp. 511-525.

Warren, P., Grabe, E. & F. Nolan: Prosody, phonology and parsing in closure ambiguities. In: Language and Cognitive Processes, 10 (1995), pp. 457-486.

Wise, R., Chollet, F., Hadar, U., Friston, K. J., Hoffner, E. & R. S. J. Frackowiak: Distribution of cortical networks involved in word comprehension and word retrieval. In: Brain, 114 (1991), pp. 1803-1817.

Zatorre, R. J., Evans, A. C., Meyer, E. & A. Gjedde: Lateralization of phonetic and pitch discrimination in speech processing. In: Science, 256 (1992), pp. 846-849.

Zatorre, R. J., Meyer, E., Gjedde, A. & A. C. Evans: PET studies of phonetic processing of speech: Review, replication, and reanalysis. In: Raichle, M. & P. S. Goldman-Rakic (eds.), Special issue: Cortical imaging – microscope of the mind. Cerebral Cortex, 6 (1996) 1; R 3 – R 4, pp. 21-30.