Language related brain potentials in patients with cortical and subcortical left hemisphere lesions

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Summary
The role of the basal ganglia in language processing is currently a matter of discussion. Therefore, patients with left frontal cortical and subcortical lesions involving the basal ganglia as well as normal controls were tested in a language comprehension paradigm. Semantically incorrect, syntactically incorrect and correct sentences were presented auditorily. Subjects were required to listen to the sentences and to judge whether the sentence heard was correct or not. Event-related potentials and reaction times were recorded while subjects heard the sentences. Three different components correlated with different language processes were considered: the so-called N400 assumed to reflect processes of semantic integration; the early left anterior negativity hypothesized to reflect processes of initial syntactic structure building; and a late positivity (P600) taken to reflect second-pass processes including re-analysis and repair. Normal participants showed the expected N400 component for semantically incorrect sentences and an early anterior negativity followed by a P600 for syntactically incorrect sentences. Patients with left frontal cortical lesions displayed an attenuated N400 component in the semantic condition. In the syntactic condition only a late positivity was observed. Patients with lesions of the basal ganglia, in contrast, showed an N400 to semantic violations and an early anterior negativity as well as a P600 to syntactic violations, comparable to normal controls. Under the assumption that the early anterior negativity reflects automatic first-pass parsing processes and the P600 component more controlled second-pass parsing processes, the present results suggest that the left frontal cortex might support early parsing processes, and that specific regions of the basal ganglia, in contrast, may not be crucial for early parsing processes during sentence comprehension.

Keywords: left hemisphere lesions; syntactic-semantic processing; event-related potentials; P600; N400

Abbreviations: AAT = Aachen Aphasia Test; ANOVA = analysis of variance; BA = Brodmann area; ELAN = early left anterior negativity; EOG = electro-oculogram; ERP = event-related brain potential

Introduction
Since the early discoveries of the language–brain relationship (Broca, 1856; Wernicke, 1874; Geschwind, 1965; Goodglass, 1993) there has been a long debate about which cortical and subcortical areas support language processes. The classical brain lesion–behaviour approaches suggest the following interpretation: patients with left hemisphere posterior (temporoparietal) lesions including Wernicke’s area speak fluently and produce at least parts of a sentence with seemingly correct syntactic structures. However, their speech and their comprehension reflect limitations to process content words such as nouns and verbs (e.g. Berndt et al., 1997). The underlying deficit in these patients has been defined either as a deficit in the semantic representation of the mental lexicon (Zurif et al., 1974) or as a deficit ‘in accessing and operating on semantic properties of the lexicon’ (Milberg and Blumstein, 1981, p. 381; Blumstein et al., 1982).

Syntactic processing has been linked with the left frontal cortex including Broca’s area, while lexical processing has been connected with the left temporal and frontal cortex (for a review, see Goodglass, 1993). In some cases, patients with frontolateral lesions in the left hemisphere produce agrammatic sentences. Short sentences in which function words and other grammatical morphemes are missing are a typical example (e.g. Goodglass, 1976). Also, formal testing that requires the correct interpretation of an underlying syntactic structure often revealed agrammatic comprehension (Caramazza and Zurif, 1976; Heilmann and Scholes, 1976). More recently, this comprehension deficit has been defined as a failure of fast access of syntactic information (Friederici, 1985; Kolk and Van Grunsven, 1985; Friederici and Kilborn, 1989; Haarmann and Kolk, 1991). In these studies it was shown that Broca patients, although delayed in their on-
line use of syntactic information, nonetheless, demonstrate syntactic knowledge as indicated by a syntactic priming effect (Friederici and Kilbourn, 1989; Haarmann and Kolk, 1991). Studies that have investigated aphasia and the particular brain structures involved, found that persisting Broca’s aphasia resulted from lesions in Broca’s area, the underlying white matter compartment and the anterior insula, but not from focal lesions in Broca’s area itself (Mohr, 1976; Dronkers et al., 1992). The combined findings suggest that the left frontolateral cortex is engaged in fast and automatic procedures necessary for normal production and comprehension, while syntactic knowledge as such may be represented elsewhere. This conclusion is further supported by studies showing that agrammatic patients are able to judge a sentence’s grammaticality (Linebarger et al., 1983).

Apart from these classical cortical language areas it has been disputed whether and to what extent subcortical areas are part of the network supporting language processing (Damasio et al., 1982; Naeser et al., 1982; Varney and Damasio, 1986; Alexander et al., 1987; Robin and Schienberg, 1990; Nadeau and Crosson, 1997). While Nadeau and Crosson (1997) deny a direct role of the basal ganglia in language processing, others assume such a direct relationship, in particular in language production (Alexander et al., 1987; Robin and Schienberg, 1990). It has been proposed that the basal ganglia might subserve the processing of grammatical information in both language production and comprehension (Lieberman et al., 1992; Grossman et al., 1993). Ullman and colleagues (Ullman et al., 1997) specified this view by suggesting that the basal ganglia together with frontal regions are supporting grammatical procedures rather than the representation of declarative grammatical knowledge. Thus, these studies suggest that the basal ganglia are involved in syntactic procedures in particular.

The brain lesion–behaviour approach has been complemented by neuroimaging studies, such as PET and functional MRI, which provide further evidence that the superior temporal gyrus and the supramarginal gyrus support lexical processes during auditory language comprehension (Petersen et al., 1989; Zatorre et al., 1996). These types of studies have led to a more detailed functional description of the frontal cortices. It appears that the Brodmann areas (BA) 45/47/46 are involved in semantic memory (Kapur et al., 1994), whereas BA 44 is active during phonologically sequencing (Buckner et al., 1995) as well as during grammatical processing (Stromswold et al., 1996). Rephrasing these latter findings it could be argued that BA 44 supports the application of phonotactic and of syntactic rules or procedures.

**Language-related brain potentials**

Although these approaches have advanced our knowledge concerning the particular subparts of the brain involved in language processing, they do not suffice to describe the interplay of different functional subsystems in time. The measurement of event-related brain potentials (ERPs), whose temporal resolution is in the millisecond domain, attempts to study the temporal course and interplay between different neurofunctional subsystems involved in language processing (Kutas and Hillyard, 1983; Neville et al., 1991; Friederici et al., 1993).

ERPs are small voltage oscillations that are measured at the scalp surface and are time-locked to the processing of external events. They involve a sequence of deflections (i.e. components) that reflect stages of information processing in the brain. Language-related ERP components with different temporal and spatial characteristics of brain activity have been identified (for an overview, see Kutas and Van Petten, 1988). Three different ERP components have been reported to correlate with different aspects of language processing during comprehension. Semantic processes are reflected in the so-called N400 component, a centroparietally distributed negativity that shows up about 400 ms after the onset of a word, which is not expected given the prior semantic context (e.g. Kutas and Hillyard, 1983). Studies that utilized intracranial electrodes recordings suggest the anterior part of the inferior temporal lobe as a possible generator for the scalp recorded N400 (Smith et al., 1986; McCarthy and Nobre, 1995; Nobre and McCarthy, 1995). Syntactic processes have been found to correlate with two scalp-recorded ERP components: a left anterior negativity either between 150 and 200 ms for phrase structure violations (e.g. Neville et al., 1991; Friederici et al., 1993) or between 300 and 500 ms for morphosyntactic agreement violations between lexical elements (e.g. subject–verb agreement) (Rosler et al., 1993; Osterhout and Mobley, 1995; Gunter et al., 1997; Munte et al., 1997; Coulson et al., 1998) and a late centroparietally distributed positivity around 600 ms, the so-called P600 (i.e. Osterhout and Holcomb, 1992). [Note that it is still a matter of debate whether the latency difference of the negativity is due to the functional distinction between the type of syntactic errors under investigation (phrase structure versus other types), and/or to the speed of the input processes (optimal, i.e. normal speech rate in auditory perception and high contrast in visual perception versus non-optimal, i.e. word-by-word presentation with pauses between each word). However, from a linguistic perspective there is a principle difference between information concerning the categorical features (word category) and the agreement features (person, number, gender and case) (Chomsky, 1995). It is not unlikely that this difference is reflected in the processes under observation.]

So far, the early left anterior negativity (ELAN) between 150 and 200 ms has only been observed with outright syntactic phrase structure violations (Neville et al., 1991; Friederici et al., 1993; Hahne and Friederici, 1999), whereas the P600 has been found with syntactically non-preferred structures as well as with outright syntactic violations (Osterhout and Holcomb, 1992; Hagoort et al., 1993). We have proposed that the two components, namely the early left anterior negativity and the P600, reflect different processing...
stages during syntactic parsing (Friederici, 1995). This proposal assumes two parsing stages: an automatic first-pass parsing stage during which the initial structure is built upon purely syntactic information and a second stage during which syntactic and semantic information is mapped onto each other (see also Frazier, 1987). It should be noted that there are a number of alternative psycholinguistic models that have been proposed during recent years. The discussion about the ultimate description of the processes underlying language comprehension is still ongoing (for a recent review, see Kempen, 1998).

Here it is assumed that the early left anterior negativity reflects initial structure building. The early stage of initial phrase structure building involves the identification of the incoming word’s syntactic category (i.e. article, noun, verb, preposition) upon which a local syntactic structure is built. For example, the sequence the man is identified as an article—noun—sequence, which can be structurally represented as a noun phrase. Other sequences are represented as verb phrases or prepositional phrases—structural chunking of this kind not only provides the parsing system with information necessary to build up structural hierarchies and relationships between various phrases (e.g. [S [NP the man] [VP [V stands] [PP on the chair]]]), it also allows the memory system to hold more information (i.e. it does not have to memorize a list of isolated words, but structured phrases). The P600 is taken to reflect secondary parsing processes including re-analysis or repair depending on whether the sentence under consideration has a correct but non-preferred structure (e.g. object-first sentences) or an incorrect structure (e.g. sentences containing an illegal sequence of words). More recently it has been proposed that the P600 is an index of the difficulty of syntactic integration processes in general, rather than of re-analysis and repair processes in particular (Kaan et al., 1998). Thus, although the functional specification of the two syntax-related ERP effects known from the literature is still ongoing, it appears that the early anterior negativity reflects a highly automatic, early process during syntactic parsing while the P600 reflects later, more controlled processes. This notion is based on the observation that the latter, in contrast to the former, is under the influence of strategic control (Coulson et al., 1998; Hahne and Friederici, 1999) and under the influence of semantic variables (Gunter et al., 1997).

One way of combining the classical but static brain lesion–behaviour approach and the more dynamic though neurotopologically less specific approach is to register event-related brain potentials in patients with focal brain lesions. This line of research has been applied quite successfully in the domain of attention and memory (Knight et al., 1989; Knight, 1997). More recently ERPs have been used in the domain of language comprehension (Hagoort et al., 1996; Swaab et al., 1997; Friederici et al., 1998). Hagoort and colleagues (Hagoort et al., 1996) and Swaab and colleagues (Swaab et al., 1997) investigated semantic aspects of language processing in aphasic patients with classified syndromes as determined by a standard aphasia test. They reported a general decrease in the N400 component in both Broca’s aphasics and Wernicke’s aphasics. However, the N400 amplitude varied as a function of the degree of the comprehension deficit in the patients. The authors concluded that ‘comprehension deficits in the aphasic patients are due to an impairment in integrating individual word meanings into an overall meaning representation’ (Hagoort et al., 1996, p. 627).

Friederici and colleagues (Friederici et al., 1998) investigated semantic and syntactic processing during language comprehension in the case of two aphasics with distinctive lesions by employing the ERP method. Although inferences on ERP data from single subjects must be interpreted with caution, we believe that the reported double dissociation is of interest. The absence of one language-related ERP component in the presence of another may suggest a processing failure in a particular language domain. Patient G.R. with a circumscribed lesion in the posterior part of the left hemisphere (involving the posterior third of the upper temporal lobe, presumably the superior temporal gyrus) and the adjacent portion of the parietal lobe (presumably the inferior angular and less likely the supramarginal gyrus) did show an ELAN, but no N400 or P600. Patient W.S. with an extended lesion restricted to the anterior part of the left hemisphere [involving the superior frontal gyrus in its full length, the middle frontal gyrus (except its most rostral portion), the opercular and an adjacent band of the triangular part of the inferior frontal gyrus, the rostral and upper insula including the external capsules, and the frontodorsal white matter down to the moderately enlarged lateral ventricle] showed an N400 component correlated with semantic processes, a P600 correlated with late syntactic processes, but no early left anterior negativity correlated with the processes of fast initial structure building. In this patient the caudate nucleus and the putamen were intact, suggesting that the observed deficit was due to the cortical lesions. From these findings we concluded that left frontal areas subserve the fast processes of initial structure building reflected in the early left anterior negativity, and that left temporoparietal areas support aspects of lexical semantic processing reflected in the N400 component. However, the nature of this lexical–semantic processing is unclear. At a functional level it was proposed that the N400 reflects processes of lexical integration rather than lexical processing per se (Chwilla et al., 1996). At a neuroanatomical level it has been claimed that the generators of the N400 are located in the anterior portion of the fusiform gyrus (McCarthy et al., 1995; Nobre and McCarthy, 1995). It remains open to discussion which aspects of lexical processing are subserved by the left superior and middle temporal gyri.

The present study
The present ERP study investigated the auditory comprehension of syntactic and semantic information in subjects with different circumscribed cortical and subcortical
lesions within the frontal areas of the left hemisphere. The experiment included aetio logically homogeneous patients who had suffered an ischaemic stroke. In addition, three patients (017, 019 and 157) showed a likely additional haemorrhagic component of the infarct. The patient groups were classified by their lesion sites: (i) patients (hereafter denoted as ‘cortical group’) with left anterior lesions including parts of the frontolateral cortex and of the neostriatum (caudate nucleus, putamen), and (ii) patients (hereafter denoted as ‘basal ganglia group’) with lesions restricted to the left basal ganglia (caudate nucleus, putamen, globus pallidus).
Given the types of violations investigated we focused on three language-related ERP components: the N400, the early left anterior negativity and the P600. Subjects listened to auditorily presented correct and incorrect sentences. The semantic condition contained sentences with selectional restriction violations, while the syntactic condition included sentences with word category violations. On the basis of a previous case study (Friederici et al., 1998) we predicted that subjects in the cortical group should show no early left anterior negativity, whereas components that reflect controlled processes such as the P600 component (second-pass syntactic processes) and the N400 component (post-lexical integration) should be present. If, however, the basal ganglia are not primarily involved in processes related to language comprehension (e.g. Nadeau and Crosson, 1997) patients with lesions restricted to the subcortical structures should demonstrate all three ERP components.

**Methods**

**Subjects**

Two groups of brain-damaged subjects and 14 non-brain-damaged controls participated in the experiment. The seven patients were classified into the two groups according to their lesion sites: (i) the cortical group included three patients with lesions including the left inferior frontal gyrus, the anterior insula and parts of the neostriatum; (ii) the basal ganglia group included four patients with exclusively subcortical lesions restricted to the caudate nucleus and/or to some parts of the lenticular nucleus. T1/T2 and 3D datasets were inspected by two experienced neuroradiologists and no cortical damage was detected in the basal ganglia group. Details concerning the patients’ lesion sites are displayed in Fig. 1 and are listed in Table 1. The individual patient history is presented in Table 2, including information about age, gender, time of stroke onset to ERP measurement, specified scores in the Aachen Aphasia Test (AAT) and premorbid handedness.

For each patient there were two control subjects matched in age and gender. They were all right-handed (Oldfield, 1971). The control group for the cortical patients consisted of four female and two male subjects with a mean age of 42.6 years (C1 = 27 years; C2 = 24 years; C3 = 42 years; C4 = 46 years; C5 = 58 years; C6 = 59 years). The control group for the basal ganglia patients consisted of two female and six male subjects with a mean age of 42.8 years (B1 = 31 years; B2 = 32 years; B3 = 33 years; B4 = 35 years; B5 = 50 years; B6 = 53 years; B7 = 53 years; B8 = 56 years). All subjects gave informed consent to participate in the study.

**Material**

The language material was similar to that used in earlier studies (Friederici et al., 1998; Groß et al., 1998; Hahne and Friederici, 1999). The auditory material was first recorded on analogue tape and then digitized (20 kHz, 12 bit resolution). The recording of the sentences was controlled for pronunciation, prosody and loudness. To ensure that listeners did not perceive any prosodic or acoustic cues prior to the critical word in the syntactically incorrect sentences, correct sentences of types (c) and (d) were recorded (see examples below). By means of an editing tool the nouns following a preposition were then spliced out from the digitized correct sentence. Again, measures were taken to control for co-articulation. Only nouns with the same phonological transitions from preposition offset to noun onset and from noun offset to participle onset were used. Mean loudness and splicing quality was assessed by an expert. No

### Table 1 Lesion sites

<table>
<thead>
<tr>
<th>Left hemisphere lesions</th>
<th>Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>009  019  102  017  048  110  157</td>
</tr>
<tr>
<td>Inferior frontal gyrus, triangular part</td>
<td>(+) (+) + - - - -</td>
</tr>
<tr>
<td>Inferior frontal gyrus, opercular part</td>
<td>+ + + + - - -</td>
</tr>
<tr>
<td>Precentral gyrus, inferior part</td>
<td>- + + + - - -</td>
</tr>
<tr>
<td>Anterior insula</td>
<td>+ (+) + - - -</td>
</tr>
<tr>
<td>Caudate nucleus</td>
<td>+ - - + + -</td>
</tr>
<tr>
<td>Putamen</td>
<td>+ + - + + +</td>
</tr>
<tr>
<td>Globus pallidus</td>
<td>- - - - - +</td>
</tr>
<tr>
<td>Anterior sub-/preinsular white matter</td>
<td>+ - (+) - - (+) -</td>
</tr>
<tr>
<td>Corona radiata</td>
<td>+ + - (+) - + -</td>
</tr>
<tr>
<td>Internal capsule, anterior limb</td>
<td>(+) - - + (+) (+) -</td>
</tr>
<tr>
<td>External capsules</td>
<td>(+) + + - (+) - -</td>
</tr>
</tbody>
</table>

Description of lesions determined by available CT scans or MRI scans for each individual patient in the cortical and basal ganglia group. + = unequivocal lesion; (+) = likely lesion; - = no lesion.

The types of violations investigated were: (a) selectional restriction violations (combinations of grammatical gender and number that are not allowed by the syntactic rules of German); (b) word category violations (words that are not permitted by the word category rules of German, e.g. “Zweitakt” (second verb) – “akt” (verb) and “Drittschleifung” (third verb) – “schleifung” (verb)). Given these violations we expected lexical integration to be absent in the cortical group and to be present in the basal ganglia group. This is consistent with evidence that the basal ganglia are involved in grammatical procedures.
significant difference in loudness between the spliced and the unspliced conditions was observed. Subjects listened to 192 sentences spoken by a trained female speaker. Half of these sentences were correct, 25% semantically incorrect and 25% syntactically incorrect. The semantic violation was due to a selectional restriction error [(a) Das Gewitter wurde gebügelt/The thunderstorm was ironed] and the syntactic violation resulted from a word category error [(b) Die Hose wurde am gebügelt/The pants was ironed (literal translation)]. A preposition such as am/on must be followed by a noun phrase. Therefore, a preposition followed by a verbform violates German phrase structure rules. Also, since German is a verb-second language the passive construction requires the verb in the sentence ending position. For example, a semantically correct form of sentence (a) would be (c) Das Hemd wurde gebügelt/The shirt was ironed. The correct counterpart of syntactically incorrect sentence (b) would be (d) Die Bluse wurde am Freitag gebügelt/The blouse was on Friday ironed (literal translation). The critical word was the same in all conditions.

Procedures
Participants were seated in a comfortable chair and listened to the stimuli via loudspeaker boxes. While listening to the sentences, subjects were instructed to fixate a small star in the middle of a CRT screen in front of them and to avoid blinking during the presentation of the star. The star appeared 500 ms prior to the auditory sentence presentation and remained on the screen until 3000 ms after the offset of a sentence. A response sign was then presented for 2000 ms. During this time subjects were required to respond via push buttons whether a sentence was correct or incorrect. The next trial started after an inter-stimulus interval of 1000 ms.

Table 2 Patient history

<table>
<thead>
<tr>
<th>Patient group</th>
<th>Classification</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Hand</th>
<th>Onset to ERP measurement</th>
<th>Token Test</th>
<th>AAT comprehension score</th>
<th>AAT auditory comprehension score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical</td>
<td>Broca</td>
<td>53</td>
<td>F</td>
<td>R</td>
<td>18 months</td>
<td>5</td>
<td>99/120</td>
<td>47/60</td>
</tr>
<tr>
<td>Patient 009</td>
<td>Residual aphasia</td>
<td>26</td>
<td>F</td>
<td>R</td>
<td>12 months</td>
<td>7</td>
<td>120/120</td>
<td>60/60</td>
</tr>
<tr>
<td>Patient 102</td>
<td>Residual aphasia</td>
<td>41</td>
<td>M</td>
<td>R</td>
<td>18 months</td>
<td>3</td>
<td>110/120</td>
<td>52/60</td>
</tr>
<tr>
<td>Basal</td>
<td>Residual aphasia</td>
<td>33</td>
<td>F</td>
<td>R</td>
<td>18 months</td>
<td>15</td>
<td>77/120</td>
<td>36/60</td>
</tr>
<tr>
<td>Patient 017</td>
<td>Residual aphasia</td>
<td>38</td>
<td>M</td>
<td>R</td>
<td>8 months</td>
<td>1</td>
<td>111/120</td>
<td>56/60</td>
</tr>
<tr>
<td>Patient 048</td>
<td>Residual aphasia</td>
<td>58</td>
<td>M</td>
<td>R</td>
<td>6 months</td>
<td>0</td>
<td>104/120</td>
<td>52/60</td>
</tr>
<tr>
<td>Patient 110</td>
<td>Residual aphasia</td>
<td>55</td>
<td>M</td>
<td>R</td>
<td>4 months</td>
<td>0</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Patient 157</td>
<td>No aphasia</td>
<td></td>
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</tbody>
</table>

Individual patient history. Patients are grouped by their lesion site. Included are the average time between the onset of the stroke to the ERP measurement. The severity of the language comprehension disorder is indicated by the number of mistakes in the Token Test: no/very mild disorder (0–6); light (7–23); severe (>40). In addition, the overall comprehension scores of the Aachen Aphasia Test (AAT) averaged across both the visual and auditory modalities are listed for each patient. The degree of the comprehension disorder is as follows: no/mild (107–120); light (90–106); middle (67–89); severe (1–66). Since the current task was an auditory sentence judgement task we also report the individual patient scores of the auditory comprehension subtest of the AAT which tests both the word and the sentence level of comprehension.

ERP recordings
The EEG was recorded with tin electrodes secured in an elastic cap. Nineteen electrodes were placed according to the International 10–20 system with the following locations: FZ, CZ, PZ, F7, F3, ATL, BL, WL, P7, P3, O1, F8, F4, ATR, BR, WR, P4, P8, O2 (cf. Sharbrough, 1991). Each EEG channel was amplified with a bandpass from DC to 40 Hz. The EEG was recorded continuously and stored for later analysis at a sampling rate of 250 Hz. Separate ERPs were averaged (100 ms post-onset stimulus baseline) for each subject at each electrode site. A post-stimulus baseline, time-locked to the onset of the critical word, rather than a prestimulus baseline was applied since different word types (auxiliary versus preposition) were used before the critical word (cf. Hahne and Friederici, 1999). All electrodes were referenced to linked mastoids and the impedance was reduced to below 5 kΩ. Both the vertical electro-oculogram (EOG) and the horizontal EOG were recorded from electrodes placed above and below the right eye and the outer canthus of each eye, respectively. Trials with eye blinks or horizontal eye movements and other artefacts were removed from the raw data prior to averaging the data. On average artefact rejection was 8% in the control groups. Since there was an increase in eye artefacts in the patient groups (up to 13%) we applied an eye artefact control measure (Pfeifer et al., 1995) to ensure that there were sufficient trials to calculate averages for correctly answered trials. To do this we recorded the EOG, applied a principal components analysis (PCA) yielding two statistically independent EOG components and determined their ‘propagation’ into the individual EEG channels via linear regression. To correct an EEG channel the corresponding PCA-transformed EOG components were weighted with the propagation factors for this channel and were finally subtracted from the EEG. The ERPs were time-
locked to the onset of the critical word in each sentence and then calculated from the onset of the critical word until 1500 ms post-stimulus onset.

**Data analysis**

**Correct responses**
Correct responses were subject to between-group (Patient versus Group) analyses of variance (ANOVARs) with a within-factor Condition (syntactic or semantic). Two separate ANOVAs were performed to assess behavioural changes due to cortical and subcortical lesions.

**ERPs**
ERP data for normal control groups and patient groups for correct responses were analysed using standard ANOVAs. Huynh–Feldt corrections (Huynh and Feldt, 1970) were applied for inappropriate degrees of freedom due to violations of the sphericity assumption. For each violation type (syntactic and semantic) an ANOVA was calculated including the between-subjects factor Group (Patient versus Control), the within-subjects factor Condition (correct/incorrect) and the within-subjects factor Electrode Site. Electrode sites for the statistical analyses were defined as regions of interest for each critical component. Critical components observed in the experiment for patient and normal control groups were an early anterior negativity, a centro-parietal positivity (P600) and a centro-parietal negativity (N400). Therefore, electrode sites for the early left anterior negativity were F7, F3, ATL, BL, for the P600 CZ, PZ, P3, P4, P7, P8, and for the N400 CZ, WL, WR, P3, PZ, P4. Prior to measuring the mean amplitude of each respective component time-windows were defined by visual inspection of the waveforms in both patient and control groups and then matched between groups for statistical analyses. The time windows for the respective statistical analyses of the components were early left anterior negativity (150–300 ms), P600 (300–800 ms) and N400 (300–600 ms). Significant interactions that included the factor Electrode Site were normalized with the McCarthy and Wood procedure (McCarthy and Wood, 1985).

**Results**

**Behavioural data**
Percentage correct responses for each subject and each condition (syntactically correct versus incorrect; semantically correct versus incorrect) are displayed in Table 3.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Correct Semantic</th>
<th>Phrase</th>
<th>Phrase</th>
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<tr>
<td>Cortical</td>
<td></td>
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</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>99</td>
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<td>98</td>
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<td>94</td>
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<td>96</td>
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Summary of the individual patient and normal control performance for the correct, semantically incorrect and syntactically incorrect conditions. Data is presented as total percentage correct.

0.50, P > 0.503), indicating that patients and controls did not differ in the amount of correct responses to syntactically correct and incorrect sentences.

The analysis of correct responses in the semantic condition revealed a main effect of Group [F(1,7) = 9.47, P < 0.017] but no main effect of Condition [F(1,7) = 0.73, P > 0.420] nor any interaction between Group and Condition [F(1,7) = 0.02, P > 0.884]. These data show that both patients and controls responded similarly to correct and incorrect semantic sentences. However, patients judged both semantically correct and incorrect sentences at a lower percentage correct rate than controls.

**Basal ganglia group and controls**
The analysis for correct responses in the syntactic condition did not reveal any main effects of Group × Condition, Group [F(1,10) = 2.49, P > 0.145], Condition [F(1,10) = 0.06, P > 0.813] or any interaction [F(1,10) = 0.47, P > 0.509]. There were no significant main effects of Group [F(1,10) = 0.18, P > 0.679] Condition [F(1,10) = 0.04, P > 0.845] nor an interaction of Group × Condition [F(1,10) = 2.19,
Fig. 2 Average ERPs for the ELAN component at selected left and right frontal/anterior sites displaying the cortical group/controls and the basal ganglia group/controls for the syntactic phrase structure violation condition. The waveforms are superimposed for the correct (continuous line) and the incorrect (dotted line) condition. The vertical lines indicate the onset of the critical word. The first 100 ms post-onset are used as a baseline. ATL = left anterior temporal electrode; ATR = right anterior temporal electrode.

$P > 0.169$] in the ANOVA analysis of correct responses in the semantic condition.

**ERPs**

ERPs are presented as average waveforms at selected electrode sites for patient groups and controls. In addition, each effect is presented as individual data for patients and controls. The grand average waveform of the ERPs for correct targets in the syntactic condition for the patient and control groups are plotted in Fig. 2 for the early anterior negativity and for the P600 in Fig. 3. ERPs for correct targets in the semantic condition for both patient and control groups are presented in Fig. 4. The early anterior negativity, P600 and N400 effects were calculated across the electrodes that defined a respective region of interest and are presented for each patient and control in Fig. 5 for the cortical group and Fig. 6 for the basal ganglia group.

Approximately 8% of the trials were rejected due to eye blinks, horizontal eye movement, or amplifier blocking in the control groups. Eye artefact control measures were applied to the raw data of each patient to increase the number of critical trials in each condition (Pfeifer et al., 1995). The early N1 and P2 components are not visible due to the fact that the critical word was presented in a continuous speech stream rather than in a word-by-word presentation mode. Visual inspection suggested that patient and control groups differed with respect to the latency and frontal distribution of the early anterior negativity (150–300 ms), while the centroparietal P600 with a mean latency between 300 and 800 ms was comparable between all groups. A negative-going wave (N400) with a mean latency of 300–600 ms occurred with a temporal-parietal bilateral distribution in all groups and was followed by a broadly distributed positive-going wave (P300). Statistical analyses revealed the following differences.

**Cortical group versus controls**

The ANOVA analysis of repeated measures for the ELAN component showed a Group $\times$ Condition interaction effect [$F(1,7) = 8.09, P < 0.024$] and a main effect for Group [$F(1,7) = 18.26, P < 0.003$]. The main effect for Condition was not significant [$F(1,7) = 1.15, P > 0.318$]. There was no interaction of the factors Group, Condition and Electrode Site [$F(3, 21) = 0.62, P > 0.607$]. Two-way ANOVAs by Group showed a Condition effect in the controls [$F(1,5) = 8.44, P > 0.033$] but not in the patients [$F(1,2) = 13.65, P > 0.066$]. This result confirms the visual observation that the cortical group does not display an early left anterior negativity.

An ANOVA for the P600 component revealed a main effect of Condition [$F(1,7) = 9.58, P > 0.017$] but no main effect of Group [$F(1,7) = 1.89, P > 0.211$] no interaction of Group $\times$ Condition [$F(1,7) = 0.05, P > 0.711$] nor an...
interaction of Group × Condition × Electrode Site \( F(5,35) = 0.46, P > 0.667 \). These results indicate that both groups show a P600.

Lastly, an ANOVA for the N400 displayed an interaction between Group × Condition × Electrode Site \( F(5,35) = 2.94, P > 0.033 \) but no main effect of Group \( F(1,7) = 1.72, P > 0.231 \). The factor Condition approached significance \( F(1,7) = 4.63, P > 0.068 \). The interaction was still significant when the mean amplitude measures were normalized (cf. McCarthy and Woods, 1985) \( F(5,35) = 2.98, P > 0.026 \). The single group analysis resulted in an interaction of Condition × Electrode Site in the controls \( F(5,25) = 5.87, P > 0.001 \); normalized \( F(5,25) = 5.75, P < 0.001 \), but not in the patients \( F(5,10) = 0.23, P > 0.704 \). The results reveal an N400 effect in the controls that is more accentuated at the right hemisphere electrode sites than at the left hemisphere electrode sites, while the analysis of the N400 in the patients did not confirm an N400 effect. However, the factor Condition approached significance in the omnibus ANOVA indicating that latency jitters in the patient group could have undermined the N400 effect (see individual patient data, Fig. 5).

**Basal ganglia group versus controls**

The repeated-measures ANOVA for the ELAN resulted in main effects of Group \( F(1,10) = 11.46, P < 0.006 \) and Condition \( F(1,10) = 19.69, P > 0.001 \), but not an interaction of Group × Condition \( F(1,10) = 0.06, P > 0.810 \) nor an interaction of Group × Condition × Electrode Site \( F(3,30) = 0.24, P > 0.716 \). Analysis by group revealed a main effect of Condition in the patient group \( F(1,3) = 10.63, P < 0.047 \) and the control group \( F(1,7) = 12.00, P < 0.010 \). Statistical analyses confirmed the visual inspection of the data with an ELAN elicited in both patient and control groups.

The ANOVA for the P600 in the syntactic violation condition revealed a main effect of Condition \( F(1,10) = 21.55, P < 0.000 \) but no main effect of Group \( F(1,10) = 0.04, P > 0.842 \). There was no interaction between Group × Condition \( F(1,10) = 0.67, P < 0.431 \) or a three-way interaction of Group × Condition × Electrode Site \( F(5,50) = 1.11, P > 0.360 \). These data support a P600 component in both groups.

Statistical analyses for the semantic violation condition resulted in a main effect of Condition \( F(1,10) = 9.34, P < 0.012 \). Again there was no main effect of Group \( F(1,10) = 1.07, P > 0.326 \) no interaction between Group × Condition \( F(1,7) = 0.00, P > 0.948 \) nor an interaction of Group × Condition × Electrode Site \( F(5,50) = 0.51, P > 0.647 \). These data confirm the visual inspection that both groups show an N400 effect in the semantic condition.
Fig. 4 Average ERPs for the N400 component at left and right centroparietal selected sites displaying the cortical group/controls and the basal ganglia group/controls for the semantic violation condition. The waveforms are superimposed for the correct (continuous line) and the incorrect (dotted line) condition. The vertical lines indicate the onset of the critical word. The first 100 ms post-onset are used as a baseline. WL = left Wernicke electrode; WR = right Wernicke electrode.

Discussion
The goal of the paper was to investigate semantic and syntactic information processing during auditory sentence comprehension in patients with predominantly cortical versus exclusively subcortical lesions in the left hemisphere. Seven patients grouped into two groups according to their lesion sites and 14 age-matched controls participated in an experiment in which correct sentences as well as semantically incorrect sentences and syntactically incorrect sentences were presented as connected speech. ERPs were registered while subjects were listening to the sentences. After each sentence subjects were asked to judge the sentence’s correctness.

Normal controls
As expected, normal subjects showed a N400 component in correlation with the processing of semantically incorrect sentences. Processing of syntactically incorrect sentences was correlated with an early anterior negativity and with a late centroparietal positivity, the P600 component. This result replicates earlier findings using similar stimulus material in auditory comprehension tasks (Friederici et al., 1993, 1996; Hahne and Friederici, 1999). The distribution of the frontal negativity for normal controls in this experiment was less lateralized than reported in the earlier studies. Although also present at right anterior electrode sites the maximum of the negativity was at left anterior electrode sites (Kotz et al., 1998). Experiments investigating the distributional differences of the early anterior negativity are currently under way. It was argued (Friederici, 1995) that these different components reflect semantic processes (N400) and two stages of syntactic processes, respectively. The early left anterior negativity was viewed to reflect an early stage of initial syntactic structure building and the P600 a second stage during which semantic and syntactic information are mapped onto each other and during which in case of a mismatch syntactic re-analysis or repair mechanisms take place.

The functional specification of the two syntactic ERP components is still under discussion. With respect to the P600 the issue has been raised whether or not it reflects a general context-updating process (e.g. Coulson et al., 1998; Osterhout, 1997). Independent of this debate the P600 has been viewed to reflect processes of syntactic re-analysis and repair (Friederici et al., 1996) or the difficulty of syntactic integration in general, independent of a sentence’s correctness or temporary ambiguity (Kaan et al., 1998). The different views, however, agree in that they assume the P600 to reflect late syntactic processes.

With respect to the early left anterior negativity it has been proposed that it might reflect processes of initial structure building (Friederici, 1995). The variation in the distribution of the early anterior negativity either showing a clear left maximum or displaying a more bilateral distribution raises the question whether the early anterior negativity is a reflection of
only one functional process. Evidence from experiments investigating the influence of prosodic information on early syntactic processes using ERPs (Jescheniak et al., 1998; Steinhauer et al., 1999) indicate an early influence of prosodic information on initial syntactic parsing and, moreover, recent functional imaging data (Steinhauer et al., 1999) suggest that these prosodic processes are supported by the right hemisphere including the right inferior frontal gyrus. If this holds true we may speculate that distributional differences in the early anterior negativity may be dependent on the extent to which early structuring of the auditory input is primarily syntactic (leading to a left maximum) or also includes aspects of prosodic structuring (leading to a more bilateral distribution). For the time being this interpretation for the distributional variation observed in normals must remain a pure hypothesis. However, its formulation allows clear predictions which can be evaluated experimentally.

**Patients**

The two patient groups demonstrate different patterns of breakdown for the three different language components. We will discuss these in turn.

**Cortical group**

For the semantic condition, these patients showed an attenuated negativity in the time window defined for the N400. Looking at the individual subject data it is apparent that the lack of statistical significance in the N400 group analysis was due to latency jitters in the patient group. This was further supported by the fact that the factor Condition in the omnibus ANOVA approached significance. When evaluating each single patient a N400-like pattern was observed for each patient, although in different time intervals.
This result is compatible with the finding of Hagoort and colleagues (Hagoort et al., 1996) who found that aphasics with minor comprehension deficits showed a N400 effect similar in size to that of the control subjects.

The early anterior negativity in the syntactic condition was absent in our cortical patients, but a P600 was found. The absence of the early anterior negativity and the presence of the P600 component was observed in each patient. [It should be noted that the absence of the early anterior negativity in this patient group and the presence of the early anterior negativity in the basal ganglia group can not be attributed to the size of the individual lesions in these two groups.] These results replicate an earlier case report of a Broca patient who did not display an early anterior negativity, though did display a P600 and an N400-like component (Friederici et al., 1998). The combined data suggest that patients with lesions in the anterior language cortex suffer from a selective impairment of the fast initial syntactic processes. In turn, we may conclude that this brain region is part of the neuronal network involved in fast syntactic procedures during normal language processing. The finding that these patients showed a P600 in the absence of a fast initial parse deserves some further discussion. How can they demonstrate a repair process (reflected by the P600), when they are not able to perform the first-pass parse reflected by the ELAN? The judgement data indicate that these patients are able to judge a sentence's grammatical correctness. The ERP data suggest that off-line grammaticality judgement does not necessarily rely on an automatic first-pass parse. Secondary processes reflected in P600 may suffice to perform such a judgment. Tentative support for this interpretation comes from a new functional specification of the P600 as a mechanism of integration that is not purely structural in nature but may involve thematic information (Kaan et al., 1998) and from earlier behavioural data with aphasics (Linebarger et al., 1983).

**Basal ganglia group**

Patients with lesions restricted to focal ischaemic/haemorrhagic lesions of the left basal ganglia display an interesting pattern with respect to the three ERP components. Whether the basal ganglia are involved in language processing has been discussed quite extensively (Damasio and Damasio, 1992; Lieberman et al., 1992; Grossman et al., 1993; Ullman et al., 1997). The present patient group appears not to differ from controls as no interaction between the factors Group and Condition were observed for any of the three ERP components. This was expected for the N400 component as processes underlying this component are thought to be supported by temporal brain structures.

Since there were different predictions of a possible involvement of the basal ganglia during syntactic processing, we conducted separate analyses for these patients and their controls for the syntactic condition. These analyses revealed the presence of the early left anterior negativity in the patients with basal ganglia involvement. The P600 component was also present, although somewhat reduced in the patients compared with normal controls. This finding suggests that at least the portions of the basal ganglia (i.e. caudate nucleus, putamen, globus pallidus) lesioned in our patient sample are not a primary part of the network supporting those language procedures that support early syntactic structure building, i.e. first-pass parsing processes. We may also conjecture that the accompanying subcortical lesions in two out of three patients of the cortical group do not account for the absence of the early anterior negativity.

This finding has to be discussed with respect to the results of Ullman and colleagues (Ullman et al., 1997). They reported that the procedural aspect of grammatical processing is correlated with relative damage to the left frontal/basal ganglia system. Our data indicate a differential involvement of the left subcortical and cortical regions in procedural aspects of grammatical processing. [It should be noted that Ullman and colleagues (Ullman et al., 1997) studied patients diagnosed with Parkinson’s and Huntington’s disease. In contrast to our present patient group with focal ischaemic/haemorrhagic vascular lesions, these patients have extended neuronal degeneration in the basal ganglia and presumably also in some cortical areas.] Ullman and colleagues (Ullman et al., 1997) had tested procedural aspects of grammatical processing using correctly and incorrectly inflected regular and irregular verbs. The frontal/basal ganglia patients demonstrated particular problems with regular compared with irregular verbs. As the former are thought to be generated by grammatical rules the authors concluded that the frontal/basal ganglia structure represent the procedural grammatical knowledge. Although the material and the task used in the study by Ullman and colleagues (Ullman et al., 1997) was different from the present study, a link can be made from their study to the present results via two recent ERP studies using stimulus material quite similar to the study by Ullman and colleagues (Ullman et al., 1997). Penke et al. (1997) reported results from a German language perception study in which correctly and incorrectly inflected regular and irregular verbs were presented in lists and in sentences. Incorrectly inflected irregular verbforms were associated with a negative waveform with a left anterior and temporal distribution starting around 200 ms extending to 500 ms. Similar results were also obtained in an other ERP study investigating the processing of regular and irregular verbs in English (Newman et al., 1998). Penke et al. (1997) take their findings to suggest a functional similarity between the application of rules of affixation (subject–verb agreement) and the application of phrase structure rules (structure building). This is an interesting proposal. The difference in the latency and the distribution of the left anterior negativity for the processing of phrase structure violations and the one for affixation raises the question whether both negativities indeed reflect the same function. If they do, then it would be difficult to explain the difference between the low performance on regular verbs in patients with lesions in the basal ganglia in the study by Ullman and colleagues (Ullman et al., 1997).
et al., 1997) and the ERP pattern seen for the basal ganglia group in the present study. Note, however, that the view would be compatible for the results reported for their patients with left frontal cortical lesions.

Under the assumption that the early left anterior negativity reflects automatic first-pass parsing processes the findings from the present ERP study suggest that these automatic parsing procedures are supported by the left frontolateral cortex whereas the basal ganglia are not necessarily involved in these automatic structure building processes (see also Friederici et al., 1998). ERP research with patients suffering from temporal lesions, in contrast, suggests that lexical–semantic integration and knowledge guided second-pass parsing primarily involve the left temporal language cortex (Revonsuo and Laine, 1996; Friederici et al., 1998). Interestingly, the latter two processes reflected by the N400 and the P600 can be distinguished at a functional level from first-pass parsing processes as they behave differently with respect to attentional aspects. Lexical–semantic processes reflected by the N400 (Chwilla et al., 1995) as well as grammatical processes reflected by the P600 (Vos et al., 1995; Coulson et al., 1998; Gunter and Friederici, 1999) involve aspects of attentional control, while first-pass parsing procedures do not (Hahne and Friederici, 1999). This functional difference is compatible with a general distinction between procedural knowledge available in automatic procedure and declarative knowledge being accessed in a more controlled manner. Results from studies with patients suffering from circumscribed brain lesions are compatible with a view that the distinction between procedural versus declarative knowledge may be mapped neuroanatomically onto left frontal versus left temporal language areas. The present ERP data even suggest a more fine-grained dissociation within the anterior part of the left hemisphere, namely between cortical areas and the basal ganglia.

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