Shirley-Ann Rüschemeyer: The Processing of Lexical Semantic and Syntactic Information in Spoken Sentences: Neuroimaging and Behavioral Studies of Native and Non-Native Speakers. Leipzig: Max Planck Institute for Human Cognitive and Brain Sciences, 2005 (MPI Series in Human Cognitive and Brain Sciences; 60)

The Processing of Lexical Semantic and Syntactic Information in Spoken Sentences:

Neuroimaging and Behavioral Studies of Native and Non-Native Speakers

Der Fakultät für
Biowissenschaften, Pharmazie und Psychologie
der Universität Leipzig
eingereichte

DISSERTATION

zur Erlangung des akademischen Grades
doctor rerum naturalium
Dr. rer. nat.

vorgelegt
von Shirley-Ann Rüschemeyer
geboren am 28. Oktober 1974 in New York, U.S.A.

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Tag der Verteidigung: Leipzig, den 10. März 2005

Many thanks to the following people, who have helped me both personally and professionally to accomplish the work put forth in this dissertation!

Prof. Angela D. Friederici and Prof. D. Yves von Cramon for their knowledgeable supervision, as well as for providing the means to conduct the experiments presented in this dissertation.

Prof. Nuria Sebastian-Galles and Prof. Daniela Perani for motivating discussions and especially for taking the time to read and evaluate this dissertation.

Dr. Christian J. Fiebach and Dr. Stephan Zysset for introducing me to the methods surrounding fMRI.

Dr. Anja Hahne and Dr. Vera Kempe for providing the initial experimental materials.

The Graduierten Kolleg *Universalität und Diversität* at the University of Leipzig.

Dr. Dirk Köster, Jutta Müller, Dr. Ina Bornkessel, Dr. Christoph Preul, Dr. Thies Jochimsen and Dr. Sonja Kotz for helpful comments and discussions along the way.

My family– Georg Rüschemeyer, my parents Oliver & Ann McBryan, my parents-in-law Christoph and Cornelia Rüschemeyer and my siblings Andrew, Jennifer and Oliver McBryan.

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Part I

Linguistic and Empirical Background

Chapter 1

Language and the Brain

1.1 Neurocognitive Approach to Understanding Language Processing

The question of how language is represented in the brain is hardly new. Our fascination with language processes is intertwined with the desire to understand the nature of human beings as a whole. It has been argued that the ability to communicate through language gave humans the evolutionary advantage over other primate species, although researchers disagree as to whether human evolution was preceeded (Hauser et al., 2002) or accompanied (Pinker & Jackendoff, in press) by linguistic ability.

Early attempts to localize language in the brain were based primarily on work with patients suffering from brain damage and subsequent loss of language (aphasia). The classical neurolinguistic models proposed by Broca, Wernicke and Lichtheim suggested that specific subcomponents of communication skills (i.e.: speaking or reading) were localized within specific cortical areas. For example, Broca's Area, constituting an ill-defined region within Brodmann's Areas (BA) 6, 44, 45 and 47 and Wernicke's Area, comprising posterior temporal and inferior parietal cortices, are two cerebral sites proposed to underlie the processing of language production and language comprehension respectively.

Newer neurocognitive models of language processing have not disregarded the insight of these older models regarding the breakdown of language function along 'action' lines. In other words, researchers today would certainly agree to a dissociation between language production and language comprehension. However, it is also generally recognized that language itself must be broken down into its basic subcomponents, or linguistic domains. Examples of such linguistic domains include phonology, semantics, syntax and prosody (Grodzinsky, 2000). A good deal of evidence has been collected, indicating that information within a given domain is processed at least partially distinctly from information coming from other domains. In fact, distinctions within individual domains (i.e.: distinctions between specific aspects of syntax processing) have also been identified (i.e.: Friederici & Meyer, 2004; Friederici, 2004) Newer neurophysiological and neuroimaging methods have allowed for the development of relatively detailed neurocognitive models of language processing (i.e.: Friederici, 2002; Ullman, 2001b). In this introductory chapter some of the background behind two methodologies, electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) and their relation to neurocognitive models of language processing will be discussed.

1.2 Methods of Investigation

1.2.1 Electroencephalogram

1.2.1.1 Nature of the Signal

The electroencephalogram (EEG) refers to a continuous waveform showing variations in voltage of electrical energy measured over the participant's scalp. Variations in voltage in the EEG are a reflection of both brain activity and a number of unrelated artifacts (i.e. muscular movement). The original EEG consists largely of background noise, uninteresting to the study of specific brain function. In order to focus in on those portions of the EEG which reflect cognitive processes, portions of the EEG, time-locked to a specific event, are averaged, causing background noise and artifacts not directly related to the event to cancel each other out, and leading to an enhancement of those portions of the signal which reliably co-occur with the event (see further Rugg & Coles, 1995).

ERPs are characterized by their latency, polarity and distribution across the scalp. Latency refers to the time between stimulus onset (the time-locked event) and the peak of the ERP-waveform. The temporal resolution of ERPs is on the order of milliseconds, making this method useful in investigating the temporal dynamics of cognitive functions. Polarity refers to the direction of the deflection, which is either positive or negative. There is no known functional relevance of ERP polarity. Distribution refers to the location of the observed deflection across the participant's scalp. The spatial resolution of ERPs is very poor. First of all, the recording electrodes are located over the participant's scalp at several centimeter's distance from the neural generators within brain tissue. Although several signal analysis programs have been developed that calculate an estimated generator location, it remains difficult to obtain a reliable localization for the generating source of ERP components. ERPs are conventionally named according to these three factors, for example the

’N400’ refers to a negative deflection of the signal (N), peaking at approximately 400 ms post stimulus onset (400), and having a broad centro-parietal distribution.

1.2.1.2 EEG and Sentence Processing

ERPs have been used successfully in recent years to investigate the temporal dynamics of language comprehension. Specifically, several ERP components have been shown to correlate with specific aspects of language comprehension (i.e.: syntactic processing vs. semantic processing). This has two crucial implications: (1) The uniqueness of ERP components related to processing of information from different linguistic domains gives credibility to the idea that these domains are truly processed individually in the brain. (2) The timing of language-related ERP-components gives some insight into the timing of the processes underlying language comprehension.

For native speakers, distinct event-related potential (ERPs) have been shown to correlate with different aspects of sentence comprehension: Phonological categorization and phoneme recognition have been postulated in different early ERP components around 150-200 ms after presentation of a word (Connolly & Phillips, 1994; Näätänen et al., 1997), semantic processing has been related to a negative wave component peaking approximately 400 ms after word presentation (N400) (Kutas & Van Petten, 1994), and syntactic processing has been postulated to be reflected in a biphasic ERP-pattern comprising of an early, automatic word category decision approximately 150 ms after word onset (E/LAN) (Friederici, 2002; Friederici et al., 1996) and a second later component peaking around 600 ms after word onset, thought to reflect processes of final syntactic integration (P600) (Friederici, 2002; Osterhout et al., 1994; Kaan et al., 2000).

Importantly, these language-related ERP-components are not specific to any one language, rather they have been observed using stimuli from many different languages, including English (Kutas & Van Petten, 1994), German (Hahne & Friederici, 1999), Dutch (Hagoort & Brown, 2000), Japanese (Nakagome et al., 2001), Hebrew (Deutsch & Bentin, 2001), and Italian (Angrilli et al., 2002). Clearly, specific components are elicited as a result of specific modification of language stimuli (i.e.: syntactic manipulation or semantic manipulation), and therefore not all components are found in each study. However, it can be said that all components have been observed in studies using language stimuli in a variety of different languages, and thus that these ERP signatures are not in any way tied to a specific language.

Non-native speakers show a slightly different pattern of ERP components in relation to language comprehension (review see Mueller, in pressa). Specifically it has been shown that the N400, elicited by semantic processing difficulties in native speakers, is also present in non-native speakers, but often slightly reduced in amplitude and slightly delayed in comparison to the response seen in natives (Weber-Fox & Neville, 1996; Hahne, 2001). ERP components elicited by syntactic processing, on the other hand are quite different in non-native speakers. Specifically, early components, thought to reflect automatic initial syntactic processing are missing in non-natives (Hahne, 2001; Kubota et al., 2003, 2004), whereas later components (P600), thought to reflect controlled processes of syntactic (re-)analysis and repair are observed in highly proficient speakers, although also with a reduced amplitude and delayed latency (Weber-Fox & Neville, 1996; Hahne, 2001; Hahne & Friederici, 2001). On the basis of such evidence it has been suggested that non-native speakers (1) processes semantic information in a manner similar to native speakers, and (2) lack the resources to instigate fast automatic syntactic processing in the same manner as native speakers, but compensate for this in slower, controlled late processing steps (Hahne, 2001).

1.2.2 Functional Magnetic Resonance Imaging

In the following a brief overview of the principles behind functional magnetic resonance imaging (fMRI) and the brain's blood oxygen level dependency (BOLD) response will be given. The principles behind magnetic resonance imaging (MRI) per se are not addressed here. Interested readers are directed towards introductory textbooks such as Jezzard, Matthews & Smith (2001) or Buxton (2002).

1.2.2.1 Nature of the Signal

Blood Oxygen Level Dependent Response
FMRI is a non-invasive method of indirectly measuring neuronal activity in the brain. It uses deoxyhemoglobin as an inherent paramagnetic contrast agent. Specifically, the localized MRI signal is dependent upon deoxyhemoglobin concentration, which in turn is a function of oxygen consumption, blood flow and blood volume. Although the precise nature of the coupling between local blood flow and neuronal activity is not understood (Matthews, 2001), substantial evidence has been collected showing that specific types of neuronal activity (local field potentials) correlate to a high degree with the BOLD response (Logothetis et al., 2001; Heeger & Ress, 2002).

The BOLD signal, upon which fMRI measurements are based, comes primarily from hydrogen protons, which are present in the water molecules of the brain. In an external magnetic field (the magnetic field is maintained by the scanner- 1.5 and 3 Tesla magnetic fields are typically used clinically and in research), a net magnetization, which is parallel to this field, is established by the nuclear magnetic moments (spins) of the protons. This is the equilibrium state. By applying a short radio-frequency pulse (excitation), it is possible to create a non-equilibrium orientation of the magnetization lying in a plane which is perpendicular to the external field. After excitation, the magnetization precesses freely in this plane while re-establishing the initial state. Thereby, a detectable radio-frequency signal is generated, which allows conclusions about the magnetic environment of the protons to be drawn. The MRI scanner measures the sum total of the emitted radio-frequency energy, which decays over time as the hydrogen protons return to their natural state.

Deoxyhemoglobin is paramagnetic, while oxyhemoglobin has no effect on the magnetic field. A high concentration of deoxyhemoglobin therefore results in local field variations in and around blood vessels. These changes, or inhomogeneities, in the magnetic field are reflected by a faster decay of in-plane magnetization, a subsequent reduction of re-elicited radio frequency signal and ultimately a lower image intensity. Therefore, an increase in deoxyhemoglobin causes a decrease in image intensity. This means that the presence of deoxyhemoglobin in a given volume of tissue leads to a decrease in signal intensity for this area. Furthermore, an increase in oxyhemoglobin brings on an increase in signal intensity. BOLD imaging therefore does not directly measure tissue perfusion, blood flow, or neuronal activity, rather it measures changes in the magnetic properties of volumes of brain tissue, which change as a function of blood flow, which is thought to correlate with neuronal activity.

The BOLD response is characterized not just by a change in signal intensity, but by a pattern of change over a period of several seconds. The classical BOLD response is characterized by three phases: (1) the initial dip, which is thought to reflect an initial period of oxygen consumption in the brain, (2) a large increase above baseline, which reflects an oversupply of oxygenated blood to the area, and (3) the return to a state just slightly below baseline as the overshoot of oxygenated blood diminishes.

Event-related fMRI makes use of the fact that the BOLD response returns to a baseline state after a period of several seconds. The ability to make use of event-related designs is a crucial advantage of fMRI over other neuroimaging techniques such as positron emission tomography (PET), which depend on blocked designs (see further Toga & Mazziotta, 2000). Clearly the temporal resolution of the BOLD response (over seconds) is not on the same scale as that measured using EEG (milliseconds). However, the spatial resolution of the information obtained from fMRI is far superior to that of EEG. High resolution MRI is capable of capturing spatial differences of as little as 1 mm, however most functional studies use a voxel size of between 3 and 5 mm.

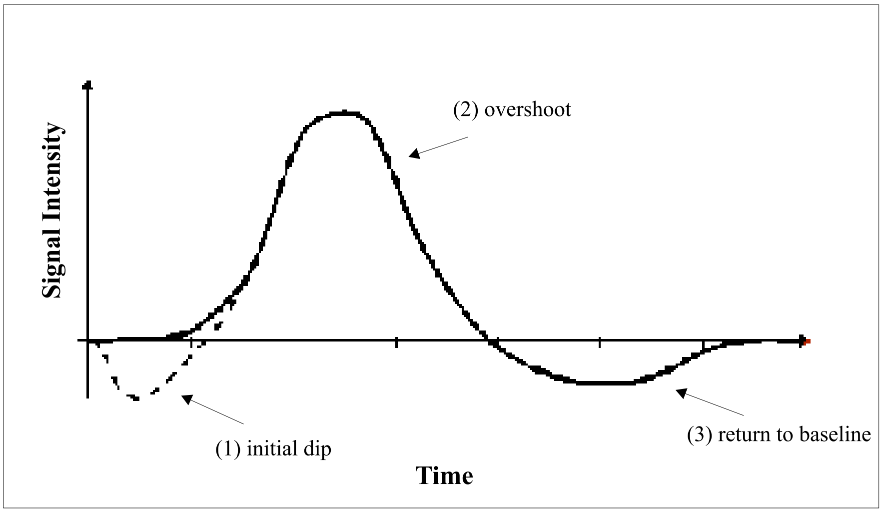

Figure 1.1: Modulated BOLD-response curve showing signal intensity over time. The response is characterized by three phases: (1) the initial dip, (2) overshoot of oxygenated blood, (3) return to baseline state.

fMRI Data Aquisition and Analysis

The data obtained from each participant consists of two high-resolution anatomical data sets and one functional data set. The first of the anatomical data sets is a high-resolution 3D MR scan of the participant's entire brain. This 3D scan is transformed into stereotachtic space and serves as a reference image for the alignment of anatomical and functional data. The 3D scan is not necessarily done in the same session as functional recordings. The second anatomical scan is taken in conjunction with the acquisition of functional data (usually directly prior to the functional scan). This is a 2D MR scan of the same anatomical slices that will be observed in the functional measurement. In other words, the 2D scan shows high-resolution anatomical structure of exactly those slices which will be excited in the functional measurement. The position of the 2D scan in relation to the 3D reference scan is compared, and a mapping of the 2D scan onto the 3D scan is saved in the form of a transformation matrix. This matrix ultimately describes how the 2D anatomical scan can be described in the stereotachtic space of the reference image. The matrix will be used in a later processing step mapping the functional data into stereotachtic space. Functional data is acquired in the same session as the 2D anatomical scan. During the functional measurement, signal intensity images are recorded from the same slices captured in the 2D anatomical scan. Images are obtained in rapid succession from all relevant slices. The measurement of all slices occurs repetitively (TR) at regular intervals (usually every 2 seconds).

The analysis of the data acquired by the MR scanner requires several stages of preprocessing followed by statistical analysis of the changes in signal intensity. Preprocessing of data is done in order (1) to correct for artifacts in the raw data resulting from technical or biological factors not related to the cognitive processes under investigation, and (2) in order to align functional and anatomic data onto a standardized coordinate system. Preprocessing of data as outlined under (1) involves first the correction of data for small movements made by the participant over the course of an experimental session. Secondly a correction of slice time acquisition is carried out, which corrects for the minimal difference in time between the acquisition of data from each slice in a given set. Lastly a baseline correction, which removes low-frequency drifts from the time series through high-pass filtering, is carried out. At this stage of processing, functional data are also generally spatially smoothed using a Gaussian filter.

Corrected functional data is then introduced into the stereotachtic space of the 3D reference brain, using the transformation matrix described previously. The data is usually additionally transformed into a normalized stereotacthic space, such as that defined by Turnoux & Talairach (1988) or MNI. This linear normalization process enables group statistics to be calculated, and facilitates the comparison of results worldwide.

After preprocessing and co-registration have spatially identified all sets of raw data, the statistical analysis of this data can begin. The raw data are introduced into the general linear model (GLM) and are convoluted with a design matrix that specifies the onsets of the different experimental manipulations as condition-specific regressors. GLM makes the important assumption that the fMRI signal is proportional to a measure of local neural activity (Heeger & Ress, 2002). The beta-coefficients obtained in this processing step are used to determine differences in the signal obtained from each voxel in correlation with the given experimental manipulation across the entire experiment. This is done by means of t-tests run on the beta-values of each voxel in correspondence with a given experimental manipulation. The result of this last step of the statistical analysis is a statistical parametric map (SPM) which contains a Z-value for each recorded voxel. Z-maps, therefore, reflect the significance of the difference between beta-values of a given voxel in relation to two experimental conditions, or to an experimental condition and zero. They do not provide information as to the absolute amount of activation in a given brain area. In order to identify those areas which show reliably different changes in signal intensity, a significance threshold is applied. For example a

Z-value of 2.32 corresponds to a p-value of 0.01; a Z-value of 2.57 corresponds to a p-value of 0.005, and the frequently used Z-value of 3.09 corresponds to a p-value of 0.001.

Clearly there is a problem of multiple comparisons in this analysis, as t-tests are performed for thousands of voxels simultaneously. A double threshold, including (1) the z-value threshold coupled with (2) a threshold concerning the size of an activated cluster of voxels helps to correct for the multiple comparisons problem.

1.2.2.2 fMRI and Sentence Processing

Functional MRI has made it possible in just the last decade to study on-line language processing *in vivo* in healthy participants. This has led to an accumulation of empirical data, however a fully satisfactory neuroanatomical model incorporating the many facets of language processing has not yet emerged. Although several studies show overlapping sites of activation in correlation with certain aspects of language processing, there are as many discrepancies. Differences may clearly be the result of different methods of analysis, language material, presentation modalities and experimental tasks. Such differences make the comparison of results from different research groups difficult. Nevertheless a review of the existing literature is clearly in order.

The neurocognitive approach to looking at language processing entails looking at different language domains separately. As pointed out previously, it is postulated that, for example, syntax, semantics, prosody and phonology are processed to some extent in isolation from one another and then reintegrated at a later stage of processing. Crucially, it is postulated that distinct cerebral networks underlie the processing of information from different linguistic domains (but see also Keller et al., 2001). The empirical work done in this thesis focuses on the processing of syntactic and semantic information within spoken sentences, and an overview of relevant neuroimaging studies exploring these two domains will be given in the following. It should be noted that this overview is not comprehensive in the sense that studies investigating other domains such as phonetics (i.e.: Binder et al., 1997, 2000; Belin et al., 2000, 2002) or prosody (Friederici & Alter, 2004) are not included.

In those studies looking specifically at syntactic processing in sentences, two central experimental designs have been implemented: (1) syntactic complexity manipulations, in which the brain's response to various levels of syntactic complexity is parametrically analyzed, and (2) violation paradigms, in which the brain's response to syntactic violations is usually compared to the response to correct sentences or another baseline task. It has been argued recently that precisely this distinction may be crucial in the localization of function within frontal cortex: Specifically, the detection of syntactic violation may involve processing of a different nature than that captured in complexity manipulations (Embick & Poeppel, 2003; Friederici, 2004). Studies examining sentence complexity will only be addressed briefly here, as the empirical work done in this thesis addresses the detection of violations in spoken language processing specifically. A more comprehensive overview of work done using violation paradigms will then be provided.

A series of studies have attempted to capture on-line syntactic processing by means of recording the brain's response to syntactic complexity. Several researchers have used subject and object relative clause constructions in order to manipulate syntactic complexity (Just et al., 1996; Stromswold et al., 1996; Caplan et al., 1998, 1999; Caplan, 2001). In the first of these studies, the event-related BOLD-response to visually presented (1a) subject relative clauses and (1b) object relative clauses was recorded using fMRI (Just et al., 1996).

(1a) The reporter that attacked the senator admitted the error.
(1b) The reporter that the senator attacked admitted the error.

Subject relative clauses are described to be less complex in their syntactic structure than object relative clauses. This is due to the fact that the underlined initial noun in subject relative clauses is both the subject of the main clause (*the reporter admitted the error*) and the relative clause (*[the reporter] that attacked the senator*). In object relative clauses, on the other hand, the initial noun is subject of the main clause (*the reporter admitted the error.*), but object of the relative clause (*[the reporter] that the senator attacked*). This additional computation is postulated to make object relative clauses more complex for the parser than subject relative clauses.

Sentences of increasing syntactic complexity as characterized by the examples above were seen to elicit more activation (as judged by volume of activation) in four regions of interest (bilateral IFG and bilateral STG) (Just et al., 1996). The interpretation of activation level based on number of activated voxels makes little sense, however this initial study gave rise to a series of other fMRI and PET studies, in which similar issues of syntactic complexity were investigated (Stromswold et al., 1996; Caplan et al., 1998, 1999; Caplan, 2001).

Caplan and colleagues also used subject and object relative clauses to manipulate syntactic complexity, however in a slightly different form than used in the study by Just and colleagues. In these studies the relative order of subject and object was manipulated to give (2a) object-subject relative clauses and (2b) subject-object relative clauses.

(2a) The child spilled the juice that stained the rug.
(2b) The juice that the child spilled stained the rug.

In both sentences the antecedent of the relative clause is the underlined noun *juice*. In subject-object relative clauses *juice* is the subject of the main clause (*the juice stained the rug*) and object of the relative clause (*[the juice] that the child spilled*); in object-subject relative clauses *juice* is object of the main clause (*the child spilled the juice*) and subject of the relative clause (*[the juice] that stained the rug*). Subject-object relative clauses are assumed to be more complex in their syntactic structure because (among other things) they contain a center-embedded relative clause, which interrupts the main clause, while object-subject relative clauses are right-branching, leaving the main clause intact (see further Gibson, 1998; Caplan, 2001). In response to the more complex subject-object sentences, Caplan and colleagues report increased levels of activation in several sites within left prefrontal cortex (within and surrounding left IFG), which Caplan broadly refers to as Broca’s Area (Caplan, 2001). The authors conclude that Broca’s Area houses the mechanism required for parsing syntactically complex structures.

Recent discussions surrounding this work have opened the question of the role of short term memory in parsing syntactic structure. Specifically, syntactic structures in which the phonological form of a word is not necessarily located at the position in which its semantic role can be filled (i.e. filler-gap distances, or transformations: see further Gibson, 1998) have been argued to draw more heavily on short term memory resources than sentences without filler-gap dependencies (Gibson, 1998). Such filler-gap dependencies were unwillingly manipulated along with syntactic complexity in the sentence materials constructed by Caplan and colleagues, as can be seen in the following examples:

(2a) The child spilled the juice that$_i$ *(i)* stained the rug.
(2b) The juice that$_i$ the child spilled *(i)* stained the rug.

Specifically, subject-object constructions, such as (2b) require the maintenance of a syntactic filler-gap relation over a longer period of time (between *that* and *(i)*) than do object-subject constructions. The maintenance of an item until its integration point has been postulated to draw on more memory resources the longer maintenance must be prolonged (what Gibson refers to as the locality effect). Therefore ’syntactic complexity’ in these sentences could also be described as a greater memory load. Several research groups have thus argued that IFG activation seen to correlate with syntactic complexity is simply the result of increased reliance on short term memory due to transformation costs (Cooke et al., 2001; Fiebach et al., 2001, 2002b; Ben-Shachar et al., 2003) (but see also Wartenburger et al., 2004).

The second major category of studies investigating syntactic processing in sentences has made use of sentences containing syntactic violations. Specifically, violation paradigms assume that the detection of a syntactic error elicits increased activation in those brain areas responsible for the processing of syntax under normal conditions. Several studies have made use of such a manipulation in various ways. Embick et al. (2000) had participants read sentences that were either correct, syntactically incorrect (word order violation) or misspelled. Analysis of the BOLD-response in four predefined regions of interest (angular gyrus [BA39/40], Wernicke's Area [BA22], bilateral IFG [BA44/45]) showed increased levels of activation in all areas in response to both erroneous conditions compared to correct sentences. Furthermore all areas showed greater amount of activation increase for syntactic anomalies than for spelling errors. This difference was greatest in left IFG, leading the authors to the conclusion that left IFG plays a unique role in the processing of syntactic structure.

Ni et al. (2000) recorded the BOLD-response of participants listening to verb phrases, which were either correct, syntactically anomalous (*Trees can grew*) or semantically anomalous (*Trees can eat*). The authors report an increased involvement for both anomaly types in several regions within frontal, parietal and temporal cortex as compared to a non-linguistic acoustic baseline stimulation. Although largely overlapping sites of increased activation are observed for syntactic and semantic anomalies, the authors suggest a specific role of IFG in syntactic processing. This conclusion is drawn based on the fact that syntactic anomalies elicted a greater change of activation in IFG than in STG, while semantic anomalies elicited a change in both IFG and STG. However, no direct comparison between the response to syntactically anomalous vs. semantically anomalous conditions is made, making it difficult to argue for a greater level of activation in response to syntactic processing.

Moro et al. (2001) and Indefrey et al. (2001) both used pseudosentences (sentences consisting of inflected wordforms with no meaning) in order to capture sentential syntactic processing while excluding semantic processing. Both studies were conducted using written sentence material and both recorded brain activity using positron emission tomography (PET). Both studies demonstrate a particular portion of prefrontal cortex to be selectively activated for the processing of syntactic anomalies in pseudosentences, while other regions within IFG are argued to support the detection of errors in general. However, the regions specified for syntax processing in the two studies do not overlap. Moro and colleagues point to a portion of deep anterior IFG (BA45), while Indefrey and colleagues refer to a region in left dorsolateral prefrontal cortex closer to BA9. Clearly differences in the native language of participants (Italian and German, respectively), the violation types and the analysis methods may have influenced the spatial variability in the results between these two studies. Also, the fact that both studies were conducted using PET reduces the spatial acuity of reported results in comparison to fMRI. Both indicate, however, a special involvement of selective portions of IFG for isolated syntactic processing.

While those studies introduced to this point argue for a specific role of left IFG in the processing of syntactic errors, a number of other violation studies provide evidence that the mere detection of syntactic violations does not elicit significantly greater levels of activation in IFG (i.e.: Kuperberg et al., 2000; Meyer et al., 2000; Newman et al., 2001; Luke et al., 2002; Friederici et al., 2003; Rüschemeyer et al., in press). Kuperberg and colleagues presented participants with spoken sentences, which were either correct, syntactically anomalous (*The man slept the guitar*), pragmatically anomalous (*The man buried the guitar*), or semantically anomalous (*The man drank the guitar*). In fact, although all three violations elicited increased levels of activation within left inferior temporal region, no areas showed a selectively greater response to syntactic anomalies than to the other experimental conditions. The authors suggest that the syntactic violation used in this study (subcategory violations) may perhaps be processed at the lexical level, and thus in a more 'semantic' manner than violations brought on by word order or phrase structure expectancies.

Meyer and colleagues presented participants with spoken sentences, some of which contained various syntactic violations (phrase structure violations and number/gender/case disagreements), and some of which were correct. In response to syntactic anomalies, participants showed increased activation within several regions along the convexity of the STG (planum polare, Heschl's Gyrus and planum temporale), but not within frontal cortex. The authors conclude that STG, in particular the anterior STG, is involved in the processing of syntactic structure in spoken language comprehension, but that frontal cortex is not greatly taxed in the processing of natural speech *per se*. The authors speculate that factors such as sentence complexity, semantic plausibility and memory load may more definitively modulate frontal cortex activity.

One last example of neuroimaging studies on syntax processing in which a violation paradigm was implemented can be found in a study in which a portion of the data presented in this thesis (Exp. 1) was presented, but using a different method of data analysis (Friederici et al., 2003). In this study we presented native speakers of German with spoken sentences, which were either correct, syntactically anomalous (phrase structure violations) or semantically anomalous and simultaneously recorded the event-related BOLD-response of participants to the various experimental conditions. The main effect of each experimental manipulation was calculated in comparison to a resting baseline, and activation levels were compared across conditions by means of a regions of interest analysis. The results indicated that the processing of correct as well as syntactically incorrect sentences draws to some degree on resources within IFG. The direct comparison of these two conditions, however, provides no indication for a significantly greater role of IFG in processing syntactic anomalies than in processing syntactically well-formed sentences (see also Rüschemeyer et al., in press). Syntactic anomalies did, however, elicit higher activation levels than correct sentences in anterior to posterior STG. Although similar results have been reported previously (i.e.: Meyer et al., 2000; Newman et al., 2001) there is a general reluctance to attribute STG with processing of syntactic structure. This will be a topic of further discussion in this dissertation.

The results of violation paradigm studies do not provide an intuitively coherent picture. First, different types of syntactic violations may be dealt with by the brain very differently. For example, as pointed out by Kuperberg and colleagues, it is possible that certain 'syntactic violations' may actually be processed at the lexical level, rather than tapping into structure processing (Kuperberg et al., 2000). This would presumably lead to a reduction in differences seen in activation elicited by 'syntactic' vs. 'semantic' violations. Secondly, many of the studies claiming to see a specific involvement of IFG for syntactic processing could be interpreted differently: For example, Embick et al. (2000) argue for a specific role of IFG in syntactic processing based on the fact that the difference in BOLD-response level between the two experimental conditions (syntactic violations and spelling violations) was greatest in this region. However, the BOLD-response was also significantly different between the two conditions in all other language areas tested (right IFG, BA22, BA39/40)– the size of the effect was simply greatest in IFG. Characteristics of the BOLD-response can vary between brain regions dramatically as a function of vascularity. It is therefore rather dangerous to interpret differences in activation levels between cerebral regions even within one participant, never mind in a group contrast. Since the difference between the conditions was significant in all regions tested, it is actually rather difficult to conclude, that syntactic anomalies *selectively* activated IFG. IFG appears to be involved in syntactic transformations and effortful syntactic processing, but not necessarily in the mere detection of syntactic violations. Temporal cortex, in particular anterior STG, appears to play a more central role in syntactic processing than generally discussed.

While the neurocorrelates of syntactic processing remain elusive, there seems to be more congruency between studies investigating sentential semantic processing. Specifically it has been proposed that posterior language areas (comprising regions within temporal and parietal cortex) as well as extrastriate regions (hippocampus and parahippocampus) subserve the long term storage of semantic information (Binder & Price, 2001), while prefrontal cortex underlies more strategic and goal-directed retrieval of semantic information and the processing of semantic relationships between words and phrases (Bookheimer, 2002). Much of the work conducted on semantic processing has been conducted at the single word level, however as the focus of the empirical work done in this thesis concerns the processing of information at the sentence level, single word studies will not be addressed here (see further Binder & Price, 2001).

Violation paradigms have been used most extensively to investigate sentential semantic processing. Following the same logic as used in the investigation of syntactic information, it is assumed that those regions involved in the processing of semantic information under normal conditions will become increasingly active upon confronting a problem. In most cases, the brain's response to semantically incongruent sentences is therefore compared to the response to semantically plausible sentences. For example, Kiehl et al. (2002) presented participants with written sentences such as (3a) and (3b) and simultaneously recorded the hemodynamic response using event-related fMRI.

(3a) The dog caught the ball in his MOUTH.
(3b) They called the police to stop the SOUP.

Sentences with semantically incongruent final words elicited increased levels of activation in comparison to congruent sentences in several regions within prefrontal, motor and temporal cortex. Specifically, increased activation was observed in the inferior frontal gyrus, spreading across the lateral fissure into anterior temporal cortex in both hemispheres In the left hemisphere prefrontal activation included lateral frontal cortex as well. The authors conclude that this activation reflects increased effort in retrieving semantic information in the face of semantic incongruence. Based on the results of several neuroimaging studies investigating semantic processing at the word level (Thompson-Schill et al., 1997; Wagner et al., 2001), this activation increase is suggested to reflect either (1) the direct effect of a more extensive search for semantic information (Thompson-Schill et al., 1997), or (2) response competition between a highly expected sentence final word, which is not presented, and the semantically incongruent, unexpected sentence final word (Wagner et al., 2001).

Newmann and colleagues (2001) presented participants with sentences such as (4a) and (4b)

(4a) Yesterday I sailed Todd's boat to China.
(4b) Yesterday I sailed Todd's hotel to China.

Sentences containing semantic incongruencies, such as (4b) elicited selectively greater levels of activation than correct sentences in several temporal and temporo-parietal regions including middle temporal gyrus (BA21), angular gyrus (BA39) and medial temporal lobe (hippocampus and parahippocampus), as well as in left prefrontal regions (BA9/46 and BA9/10). The authors suggest that the presentation of incongruous words in sentences elicits activation within a greater semantic network: Posterior temporal, temporo-parietal and extrastriate areas are suggested to support the actual representation of lexical meaning, whereas prefrontal regions reflect difficulty in integrating the retrieved semantic meaning of the anomalous word into sentence context (Newman et al., 2001).

Semantic incongruencies were also included in several of the studies introduced previously (Ni et al., 2000; Kuperberg et al., 2000; Friederici et al., 2003). Ni et al. (2000), using spoken sentences, report increased activation for semantic anomalies in bilateral IFG, posterior STG, medial frontal gyrus. Kuperberg et al. (2000) report a greater involvement of bilateral STG in the processing of semantic anomalies than syntactic anomalies. Friederici et al. (2003) report activation increases in the baseline contrast for semantic anomalies in bilateral insular cortex and bilateral mid to posterior STG. The direct contrast between semantic anomalies and correct sentences was seen to elicit more activation in lateral prefrontal cortex and a region in posterior STS/MTG (Rüschemeyer et al., in press).

One very elegant study on the use of syntactic and semantic processing in sentences used a completely different experimental design to those presented above. In this study, Dapretto & Bookheimer (1999) presented participants with sentence pairs and asked them to indicate whether the two sentences were the same (S) or different (D) in meaning. In the syntactic condition the relationship between two sentences could be extracted only on the basis of syntactic information, as content words were identical (see left column below). In the semantic condition the syntactic structure of the two sentences was identical, and participants were forced to extract semantic information from the two sentences in order to make their judgment (right column below).

	Syntactic Condition	Semantic Condition
S	The policeman arrested the thief.	The lawyer questioned the witness.
	The thief was arrested by the policeman.	The attorney questioned the witness.
D	The teacher was outsmarted by the student.	The man was attacked by the doberman.
	The teacher outsmarted the student.	The man was attacked by the pitbull.

In comparison to a resting baseline, both conditions show increased levels of activation in bilateral IFG and bilateral temporo-parietal cortex (supramarginal and angular gyri), with a greater extent of activation seen in the left hemisphere. The baseline contrast of the syntactic condition showed a focus of activation within IFG in left BA45, whereas the baseline contrast for the semantic condition elicited local maxima in BA47, bilaterally. The direct contrast between activation elicited by these two conditions supported the initial observation: Left BA45 was seen to be more greatly activated for the syntactic condition, whereas bilateral BA47 was seen to be more greatly activated for the semantic condition. The authors propose that a functional distinction be made between specific regions within IFG. Specifically it is proposed that both syntactic and semantic processing relies on resources supported by IFG, but on different portions.

Taken together the neuroimaging data from sentence comprehension studies support the importance of a fronto-temporal network underlying language comprehension. However, a strictly modular view of language processing, in which syntax is housed in a particular region and semantics in another is not supported. Rather, the processing of multiple domains appears to rely on a network of resources throughout the language areas. Frontal language regions are proposed to support controlled, perhaps short term memory-related computational processing steps in language processing. In the syntactic domain this may be related to transformational processing or to additional recruitment of working memory resources. In the semantic domain this refers to effort of retrieval or selection difficulties. Posterior, temporal, temporo-parietal and medial temporal language areas are thought to reflect more long-term representations of language. In the syntactic domain this may refer to the storage of morphosyntactic information attached to lexical items, necessary for fitting words into sentence structure, or to storage of general phrase structure information, allowing for the construction of phrase structure expectancies. In the semantic domain this refers to the long-term storage of conceptual information. However, specific regions within frontal and temporal cortex may be specialized to selectively process information from different domains. Specifically it is suggested that syntax processing relies on more posterior portions of IFG (BA44/45) and anterior to mid portions of STG (BA22/42), while semantic processing draws more heavily on anterior portions of IFG (BA45/47) and middle and inferior temporal cortex and the medial temporal lobe.

Such an exact parcellation of language processing steps is, however, yet in the speculative phase. Issues related to the reliability of localization in group studies due to both interindividual variability as well as spatial smoothing steps undertaken in fMRI preprocessing must be addressed more strictly. In other words, it is not clear to what extent minimal spatial differences are reliable in studies in which the results from several participants are averaged. Furthermore, many fMRI studies have been conducted using tried-and-true experimental materials from previous behavioral and electrophysiological experiments. Because the temporal dynamics is so fundamentally different between the EEG and the BOLD signal, it is worth considering whether or not such designs are optimal for fMRI studies.

Chapter 2

Neuroimaging Studies on Bilingualism

The following chapter provides a review of current neuroimaging studies on bilingual language processing. Due to several methodological issues, including the lack of formal definitions regarding what constitutes a bilingual, a unified account of results is impossible. However, in compiling results and conclusions from studies looking at a variety of different participant groups, language pairs and modalities, several interesting general trends come to light.

First of all a major delineation has to made between those studies looking at bilingual language production and bilingual language comprehension. Many neuroimaging studies focusing on language production have methodological problems in that covert language production is generally used to minimize movement artefacts in the scanner. This obviously restricts the extent to which the experimenter can be sure of what his/her participants are actually producing during scanning. On the other hand, most of the bilingual language production studies have been conducted using various forms of the covert word production task, which makes comparisons across studies possible. The fact that different studies somewhat replicate one another speaks for the reliability of the results obtained.

Bilingual language comprehension studies, in contrast, make use of very controlled stimulus input, however few studies have tested participants with comparable stimuli, rendering the comparison of results from different labs virtually impossible. In the domain of language comprehension a further dissociation must be made between studies conducted with language stimuli in the auditory modality vs. those studies conducted using visually presented language stimuli. In the following chapter a comprehensive review of the literature available is provided broken down along the following lines: 1) studies addressing bilingual language production, and (2) studies addressing comprehension. Within the comprehension section a further breakdown is made between spoken and written language processing. Studies addressing the processing of spoken vs. sign languages are not addressed here.

2.1 Production

Language production studies in bilinguals have almost exclusively been conducted using covert, cued word generation tasks (exception: Kim et al., 1997), and can therefore be relatively nicely compared with one another. The existing studies come to relatively comparable conclusions, namely involvement of the classical perisylvian language areas in production of L1, and the recruitment of additional frontal cortical and sub-cortical areas in the production of L2 (Klein et al., 1994, 1995; Yetkin et al., 1996; Kim et al., 1997; Perani et al., 2003, but see also Chee et al., 1999b).

Klein and colleagues conducted a series of PET studies, in which the cerebral areas underlying word generation in L1 and L2 were examined (Klein et al., 1994, 1995). In the first of these studies, participants were required simply to repeat words heard in L1 (English) and L2 (French) (Klein et al., 1994). A single cerebral area, the left putamen, demonstrated differential activity, namely greater activation for repetition of words in L2 than in L1. The authors conclude that the left putamen is involved specifically in the production of L2, reflecting increased articulatory demands of speaking a language learned late in life. Klein et al. (1995) went on to investigate word generation in L1 and L2 prompted by various cues (phonological cue, semantic cue, translation). The repetition task from Klein et al. (1994) served in this study as a baseline. The goal of this study was first of all to determine whether lexical retrieval guided by phonological cues differs from lexical retrieval guided by semantic cues. Secondly the authors proposed that phonological and semantic cues might differentially affect word retrieval based on whether or not the language used was the speaker's L1 or L2. The results showed overlapping areas within left IFG to be involved in word generation, independent of how participants were cued. This was true for word generation in both L1 and L2. Since direct comparisons were not made between languages, no comment can be made as to whether levels of activation differed in response to production of words in L1 or L2. A third condition, in which participants were asked to produce translation equivalents of given words (both from L1 to L2 and from L2 to L1) did, however, show an interesting dissociation between languages. Basal ganglia structures, specifically a region within the left putamen was observed to be active in participants translating from L1 into L2, but not for translation from L2 into L1. The authors interpret this finding as further support for their belief that basal ganglia structures are more heavily relied on in the production of L2 due to problems in articulation of L2.

Two further neuroimaging studies directly compared levels of activation between word generation in L1 and in L2 cued by an initial letter (Yetkin et al., 1996; Perani et al., 2003). Both studies come to the conclusion that word generation in a subsequently learned language elicits activation in a broader network of cerebral areas than does word generation in the first learned language. Yetkin et al. (1996) used fMRI to compare activation correlated with the generation of words in a language spoken fluently (L1 or L2) spoken by a multilingual participant to activation correlated with the generation of words in a non-fluent language (L3). Participants were asked to covertly produce words beginning with a given letter in each of the three languages. The authors report greater variability in the cortical regions involved, as well as higher levels of activation during word production in the language in which the participant was not fluent. Similarly, Perani and colleagues (2003) investigated word production in highly fluent bilinguals. Importantly, participants acquired their L2 subsequently (not in parallel) to L1, and all participants reported using their L1 more often than L2. The results show no areas of greater activation for L1 than L2. Word generation in L2, however, brought on greater levels of increased activation in several left frontal regions (BA45, BA46/10, left insular cortex). The authors interpret their results as showing (1) that differences in the cerebral areas involved in processing two languages can differ, even if the proficiency of the speaker is comparable in both languages; (2) that exposure to a language is the crucial factor in determining efficiency of processing. The language to which participants were less exposed involved additional prefrontal cortices in a word generation task. This difference in activation in prefrontal cortex is explained as reflecting the additional effort involved in generating words in the language less frequently used. The authors conclude that lexical retrieval in L2 requires extra resources, however no direct evidence for processes of lexical retrieval (vs. phoneme retrieval) is provided.

Although these word generation studies do not provide identical results, a general trend does seem to be present in the data. First of all, the language used less by participants appears to employ additional cortical resources. In the studies by Klein and colleagues (1994, 1995) word generation in L2 elicited basal ganglia activation not observed in the generation of words in L1. In the Yetkin et al. (1996) and Perani et al. (2003) studies word generation in the less frequently used language elicited increased levels of activation primarily in frontal cortex. While Yetkin and colleagues report no differences between word generation in L1 and L2, it must be noted that in this study English was always labelled L1, regardless of which language the participant actually acquired first. The lack of difference reported for

Table 2.1: Overview of neuroimaging studies addressing L2 language production.

Production Studies			
Authors	Method	Task	Summary of Results
Chee et al. (1999b)	fMRI	Cued word generation	Differences in magnitude of activation in L1 and L2. No differences in peak location.
Kim et al. (1997)	fMRI	Covert production	L1 and L2 same with early AoA. Late AoA affects language organization in frontal, but not in temporal regions.
Klein et al. (1994)	PET	Cued word generation	Left putamen shows greater activation for L1 than L2.
Klein et al. (1995)	PET	Cued word generation	Increased activation in left IFG for phon and sem task in L1 and L2. BG active in translation from L1 to L2.
Perani et al. (2003)	fMRI	Cued word generation	L1 differs from L2 regardless of AoA. Exposure determines cerebral organization.
Yetkin et al. (1996)	fMRI	Cued word generation	More activation for less fluent language.

the processing of the two languages in which participants were fluent (namely L1 and L2) is thus absolutely confounded. The differences reported by the authors refer to differences between L1 and L3, which the authors interpret as correlating with proficiency. Perani and colleagues take the issue one step further to show that proficiency alone cannot explain differences in the data, rather exposure to a given language is crucial in determining the cerebral organization of language production. Secondly, it is interesting that those areas seen to be more active during generation of words in the less frequently used, less fluent language are always explained with motor control and articulation difficulties in associated with speaking a second language.

One further study, which should be mentioned here, focused on global language production rather than word generation (Kim et al., 1997). In this fMRI study, bilingual participants with different AoAs were scanned while covertly producing speech in L1 or L2. The authors report overlapping areas of activation in posterior language areas regardless of AoA, which is interpreted as evidence for a single cortical area supporting semantic processing in both languages. In the left IFG (BA44) activation elicited by L1 and L2 overlaps in participants with early AoAs, but is distinct for L1 and L2 in late learners. This dissociation is interpreted as evidence for a shared cortical network underlying syntactic processing in L1 and L2 in early bilinguals, and separate syntactic systems for L1 and L2 in late learners of a second language. The results of this study should be interpreted with caution as (1) the number of participants was extremely limited, (2) there was little to no attention paid to what languages were spoken by participants (i.e.: Turkish/English bilinguals compared directly with Italian/German bilinguals), (3) there is absolutely no control over the task, and (4) ”distinct”language areas within IFG are 4 to 11 mm apart from one another. Functional slices were measured with an in-plane resolution of 1.6 mm x 1.6 mm and a 4.5 mm interslice gap. This means that each voxel was 11.5 mm^3, which makes it difficult to argue on the level of 4 mm differences. Furthermore even if a 1 mm^3 functional resolution were available, it is not clear to what degree such anatomical specificity should be interpreted with fMRI, as only an *indirect* measurement of neuronal activity can be captured by the BOLD response (Heeger & Ress, 2002). Nevertheless it is interesting that the dissociation observed between L1 and L2 in less fluent bilinguals is within left IFG, the same area in which the studies mentioned above also report different activation patterns and levels for word generation in L1 and L2 (Yetkin et al., 1996; Perani et al., 2003).

2.2 Comprehension

Neuroimaging studies looking at comprehension of L1 and L2 are far less uniform in their results. This probably can be attributed in part to the high degree of variability in the tasks performed by participants, and in part to the very different nature of on-line language comprehension as compared to production. For example in covert production studies, the participant's possible use of ungrammatical items in L2 is undetectable, in comprehension studies, it is often the detection of these very errors, which a speaker might well produce him/herself, which is used to elicit a differential response. An overview of the comprehension literature is quite difficult to structure. One logical line of argument has been established over a number of PET studies by Perani and colleagues (Perani et al., 1996; Dehaene et al., 1997; Perani et al., 1998; Wartenburger et al., 2003), which seems to explain a large portion of the data available. Perani's research focuses on how different descriptive exogenous factors pertaining to bilinguals themselves (i.e.: proficiency level, AoA or amount of exposure to a given language) affect the neural organization of language. With the exception of one study (Wartenburger et al., 2003), this research has investigated language comprehension of spoken sentences. A different approach is taken by Chee and colleagues as well as other researchers, who in a number of experiments focus on the processing of typologically different languages (Chee et al., 1999a, 2000, 2003; Ding et al., 2003; Tan et al., 2003). This line of research has been conducted primarily with visual language stimuli, making direct comparisons between the two research areas rather difficult. The results are contradictory, Perani et al. maintaining that differences can be seen in the cerebral organization of native vs. non-native languages, and Chee et al. arguing for common neural networks. However, it is possible that this could be attributed to the modality difference in stimulus presentation.

2.2.1 Auditory Language Comprehension

In the first of a series of PET experiments looking at auditory processing of L1 and L2, Perani et al. (1996) reported differences in the cerebral areas observed to be involved in the processing of stories in L1 and L2. Specifically late learners of English (Italian native speakers) were scanned while listening to stories in Italian (L1), English (L2), Japanese (unknown to participants) and a backwards language condition, which served as a baseline condition to control for global auditory processing of speech cues. Surprisingly the authors report greater levels of activation for participants listening to L1 than to L2 throughout the perisylvian language cortex. Higher levels of activation in response to L1 are surprising given

Table 2.2: Overview of neuroimaging studies addressing L2 language comprehension.

Comprehension Studies				
Authors	Method	Modality	Task	Summary of Results
Chee et al. (1999a)	fMRI	Visual	Compreh.	Common neural networks activated for reading Chinese and English sentences.
Chee et al. (2000)	fMRI	Visual	Semantic Categorization	Character processing more similar to reading English words than to picture naming.
Chee et al. (2003)	fMRI	Visual	Same/Diff. Comparison	Repetition priming effects between translation equivalents.
Dehaene et al. (1997)	fMRI	Auditory	Passive Listening	More cortical variability for L2 than L1.
Ding et al. (2003)	fMRI	Visual	Semantic Categorization	L2 elicits more RH activation.
Illes et al. (1999)	fMRI	Visual	Lexical Decision	Semantic decision task elicits greater activation in bilateral frontal regions in L1 and L2. Common semantic storage system.
Luke et al. (2002)	fMRI	Visual	Grammaticality Judgment	L1 reading mechanisms used to read in L2.
Marian et al. (2003)	fMRI	Mixed	Lexical Decision	Phonological task: L1 and L2 show activation in IFG and STG. Local maxima are distinct between L1 and L2 in IFG, and activation level is higher for L2 than L1, not so in STG. Lexcial task: Both langauges elicit activation in IFG, L2 shows more activation than. Local maxima within IFG are distinct for L1 and L2.
Perani et al. (1996)	PET	Auditory	Passive Listening	More activation for L1 than L2. AoA affects cortical representation of language.
Perani et al. (1998)	PET	Auditory	Passive Listening	Proficiency affects cortical representation of L1 and L2 to a greater degree than AoA.
Tan et al. (2003)	fMRI	Visual	Rhyme Judgment	Common network activated in reading L1 (Chinese) and L2 (English). Different networks activated for reading L1 (Chinese) and L1 (English).
Wartenburger et al. (2003)	fMRI	Visual	Sentence Grammaticality Judgment	Cortical representation of syntax affected by AoA; cortical representation of semantics affected by proficiency.

that more effort is involved in processing a non-native language (as shown in behavioral studies).

A possible explanation for the unexpected results obtained by Perani and colleagues is provided in an fMRI study using the same sentence materials (Dehaene et al., 1997). Here the intersubject variability of increased activation was examined across participants rather than for the entire group. This was obtained by plotting local maxima for each individual participant. The results show that local maxima activated by stories in L1 overlap across participants more stably than local maxima activated by stories in L2. The authors argue that group statistics showing greater levels of activation for L1 may thus be the result of less variability in the cortical areas subserving native language processing. Less spatial variability leads to increasing overlap of activated cortical areas, which leads to a robust signal in the group average. Processing of a non-native language, on the other hand, does not necessarily recruit less cortical resources, rather the neural substrates serving the non-native language are spread out over a larger area. Greater spatial variability leads to less overlap of activated areas, and thus to an overall decrease in signal in comparison to native speakers. The authors argue that non-native language processing recruits spatially more dispersed cortical areas. This dispersion is also particularly evident within the right hemisphere.

Both of these first two studies argue that differences do exist in the neural organization of systems underlying the processing of spoken L1 and L2. While Perani et al. (1996), showed greater levels of activation for speakers listening to L1 than to L2, Dehaene et al. (1997) questions the reliability of the quantitative difference observed by Perani et al., and demonstrates that more spatially dispersed and less well-defined cortical networks may underlie processing of a second language. A further study investigating lexical and phonological processing in L2 speakers also reports greater levels of activation, in particular within frontal cortices, for processing a non-native language vs. a native language (Marian et al., 2003).

Having determined that differences in the cerebral organization of processing L1 and L2 *can* exist, it is interesting to look at what factors play a role in influencing observed differences. A number of exogenous factors concerning participants have been implicated in determining neural organization of L1 and L2 processing. Among such factors are the age at which an L2 speaker acquires his/her second language (age of acquisition: AoA), the speaker's level of attained proficiency in L2, and the amount of time a bilingual speaker spends immersed in each language environment (exposure level).

Age of acquisition has long been thought to play a crucial role in determining language abilities. The critical period hypothesis proposed by Lenneberg (1967) suggests that certain cognitive abilities, including language, must be acquired before a certain age (approximately puberty) if native-like proficiency is to be obtained. After puberty (the 'critical period') a vast reduction in neural plasticity is postulated to make the acquisition of certain abilities highly unlikely. Several behavioral and ERP-studies have maintained that the age of L2 acquisition more strongly affects some aspects of language processing than others. Specifically, phoneme and syntax processing appear to be more strongly affected by AoA than semantic knowledge (Weber-Fox & Neville, 1996; Flege et al., 1999; Hahne, 2001). Although it is generally the case that late learners of L2 do not achieve native-like proficiency, some exceptional cases are reported in the literature. Moreover late learners of a second language can achieve quite a high level of proficiency, even if they are not to be confused with native speakers.

Understandably, many studies looking at bilingual language processing have confounded AoA and proficiency level, as those participants who have learned a second language later in life are generally also less proficient in their L2. Perani et al. (1998) attempted to address this issue by using PET to examine bilingual groups with different proficiency levels (high or low) and AoAs (late or early). Participants again listened to stories in each of their languages plus a third unknown language. The results suggest that proficiency level is more important than AoA in determining cerebral representation of a language. Highly proficient L2-speakers showed largely comparable sites of activation for the processing of both L1 and L2, regardless of when they had acquired their L2. This was not the case for participants who had acquired their L2 later in life *and* demonstrated a low level of proficiency. This group showed clear differences in the processing of L1 and L2. Those regions seen activated for the processing of L1 were comparable to regions activated in the high proficiency groups. Regions activated for the processing of L2, however, differed. It should be noted that although largely comparable areas were seen activated between L1 and L2 in the high proficiency groups, some differences were actually reported between L1 and L2 in the group of early learners only. These differences were characterized by a greater involvement of right temporal cortex for L1 story processing and of hippocampal structures and superior parietal cortex for L2 story processing. Since the high proficiency groups, which differed with respect to AoA, showed comparable patterns of activation, the authors suggest that proficiency in a second language is more important in determining cerebral organization of language processing systems than is age of acquisition. Fitting with the same line of argumentation, the late acquisition groups in this study, which differed with respect to their proficiency levels, showed different patterns of cerebral activation.

The results from auditory language comprehension studies thus seem to indicate that non-native speakers rely at least to some extent on different cortical networks than native speakers to support auditory language comprehension. Furthermore the neural networks supporting processing of specific linguistic aspects (syntax vs. semantics) can differ as a function of different exogenous features related to speakers.

2.2.2 Written Language Comprehension

As mentioned above, AoA appears to affect different aspects of language processing differently. Phoneme and syntax processing seem to be particularly susceptible to effects of AoA, while semantic processing is less affected. A recent fMRI study has shown that the cerebral correlates underlying these different linguistic areas (i.e.: syntax and semantics) also differ as a function of AoA and proficiency level (Wartenburger et al., 2003). In this study written sentences were used to identify neural substrates of language comprehension in Italian-German bilinguals of different proficiency levels. Sentence materials were in German and Italian, and consisted of correct sentences, grammatically incorrect sentences (violations included number, case and gender disagreements), and semantically incorrect sentences. The participants in this study were broken down into three groups according to the age at which they acquired their second language and their proficiency level. When confronted with grammatically incorrect sentences, highly proficient non-native speakers, who acquired their second language late in life, showed a greater increase in activation in the bilateral IFG (BA44) than those speakers, who had acquired L2 early in life. This group additionally showed increased levels of activation when compared to less proficient speakers with a comparable age of acquisition in the left temporo-parietal region, right parietal lobe and right lingual gyrus. When confronted with semantically incorrect sentences, highly proficient speakers showed no differences in activation patterns, regardless of age of acquisition. Differences could be observed, however, when participants with different proficiency levels were directly compared with one another. These differences were located primarily within frontal cortex. The authors conclude that the age at which a second language is acquired plays a decisive role in determining how syntactic structure is processed in the brain, as participants with comparable proficiency levels, but different AoAs show different patterns of brain activation when confronted with syntactic anomalies. In the processing of semantic anomalies, on the other hand, attained proficiency in a second language appears to be the crucial factor in determining how cerebral networks underlying comprehension are organized.

A separate line of research has investigated bilingual processing of different orthographic systems. Much of this work has been done with Chinese-English bilinguals. In contrast to Chinese characters, which have no relation to the phonological properties of the words they represent, English graphemes are made up of letters from an alphabet which (with some regularity) can be converted to phonemes, giving insight into the pronunciation of the word as a whole. It has been proposed that reading in Chinese and English might therefore depend on different strategies, which could be represented differently within the cerebral cortex. Furthermore it has been suggested that the processing of Chinese characters might be more similar to picture naming than reading of an alphabetic script.

Chee et al. (2000) investigated precisely this issue by using fMRI to record the hemodynamic response of Chinese-English bilinguals while participants made either semantic or perceptual size judgements with Chinese characters, English words and pictures. The results indicate that while many overlapping areas support the processing of all three stimulus conditions, the processing of Chinese characters has more in common with the reading of English words than with picture naming. Similar results (namely common neural networks underlying the processing of Chinese and English stimuli) were reported in a further study conducted at the sentence level (Chee et al., 1999a).

Evidence also exists for a common semantic storage space accessed by visual input from both languages. Chee et al. (2003) utilized a word-repetition paradigm, in which repeated presentation of a word elicits relatively less increase in the MR signal. Word pairs were presented to participants in which the two word forms had either identical meanings or were non-synonymous. This was achieved across the two languages, so that identical word pairs could be made up of either (1) the same word form written in the same language but a different font (table vs. TABLE), or (2) translation equivalent word pairs (mian-bao and BREAD). Repetition priming effects (a relative decrease in the BOLD signal correlated with presentation of the second word) were observed in left pre-frontal and temporal areas regardless of whether the first and second items belonged to the same language. In other words, repetition priming effects were evident between phonologically identical items from the same language, but also between translation equivalents. The authors interpret their results as indicating that both languages are supported by a common semantic system. Although areas modulated by repetition priming overlapped spatially in the single language and mixed language conditions, the extent of activation was much greater in the mixed language condition. The authors interpret this as reflecting the additional processing cost incurred in the mixed-language condition by switching between L1 and L2. The second word in presented word pairs was always English in this experiment, meaning that single language trials were also necessarily only in English (no Chinese-only trials). Further support for a common semantic storage system underlying both L1 and L2 comes from a study conducted with proficient Spanish-English bilinguals (Illes et al., 1999).

In contrast to those studies looking at spoken language processing of L1 and L2, written language processing of two languages, even between very different orthographic systems, appears to be supported by a common cortical network (but see also: Ding et al., 2003). One explanation for the lack of observed differences may lie in the fact that most research in this domain has been conducted on the lexical (word) level, whereas bilingual language processing in the auditory domain has tended to focus on the discourse/sentence level. There is accumulating evidence in favor of a shared lexical storage system for words in L1 and L2 (French & Jacquet, 2004), and this may very well explain much of the discrepancy between results from auditory vs. visual bilingual language studies.

Based on the different information types encoded in Chinese and English scripts however, it is still rather surprising that so few differences exist in the strategies used by bilinguals of these two languages in deciphering written words. One possible explanation may be found, however, in the dual route model of visual word recognition (e.g.: Coltheart et al., 1993). In this model it is suggested that even in languages characterized by alphabetic scripts, some words may be accessed via a 'direct' route, which could in some respects be similar to Chinese character reading. The dual route model proposes the existence of two routes by which words in the mental lexicon can be accessed– one route by which novel and low frequency words are processed, in which graphemes are converted to phonemes, and a phonologically guided search of the mental lexicon is initiated; and a second, faster route by which high frequency words are processed, in which a direct grapheme-to-phoneme conversion is no longer necessary, and wordforms are retrieved without any additional grapheme-to-phoneme conversion processes. Evidence for different neural correlates underlying these two routes is also available (Fiebach et al., 2002a). In the studies discussed here, the processing of high frequency words in English might very well resemble the processing of characters in Chinese, despite orthographic differences. If the visually presented stimuli used contained predominantly high frequency words in English, it may not be surprising that processing strategies are so similar between Chinese and English.

A second explanation proposes that neural networks supporting reading do differ between monolingual speakers of Chinese and English, but that in bilingual speakers, neural mechanisms supporting reading in L1 are implemented in reading L2 (Tan et al., 2003; Luke et al., 2002). In a recent study Tan et al. (2003) was able to show that similar cerebral regions were activated in Chinese-English bilingual participants during the processing of visually presented stimuli in Chinese and in English. However, the observed pattern of activation was different for monolingual speakers of English. Thus, the authors conclude that neural processing supporting reading in L1 are taken over to support reading in L2. Luke et al.

(2002) come to a similar conclusion using visually presented two word sentences. Sentences were either grammatically and semantically well-formed, grammatically anomalous, or semantically anomalous. The results show only small regions of differential activation when participants were presented with the different anomaly types. The following conclusion is drawn: Due to properties of the Chinese language, syntax and semantics are processed by native Chinese speakers in a manner much more similar to that observed in language processing in other languages (e.g.: for evidence for a neural dissociation between syntactic and semantic processing in German see Meyer et al., 2000; Friederici et al., 2003). Furthermore native speakers of Chinese use common cortical networks to solve linguistic tasks in both Chinese and English. This suggests that although native speakers of English might process visual language stimuli differently (as seen in Tan et al., 2003), native Chinese speakers with English as a second language employ the same neural networks used to process Chinese sentences in the reading of English sentences.

2.3 Conclusion

In conclusion, a overview of the current literature reveals a number of general trends. First of all production of L1 appears to rely on different cortical networks than production of L2. Most significantly, more activation has been reported for the production of words in L2 in subcortical structures of the basal ganglia and portions of frontal cortex. Secondly, comprehension of L1 and L2 appears to be structured differently depending on what modality language stimuli are presented in. Auditory comprehension studies show a dissociation between L1 and L2 processing– L2 employing a more variable network of cortical areas, and differentially affected by exogenous factors such as age of L2 acquisition and proficiency level. Comprehension of visually presented language materials, on the other hand, appears to be processed in a more uniform matter across languages. One possible reason for this discrepancy in the results from the auditory and visual domains is the focus within each domain on language materials from different linguistic levels. Auditory language comprehension has been investigated primarily at the discourse level, while visual language comprehension has tended to rely on single words. It is, however, also possible that neural networks supporting reading in L1 are transferred to support the reading of L2 later in life, regardless of differences in language surface features. In this case, reading L2 is supported largely by predefined structures, which support reading in L1, regardless of language typology or orthography.

Chapter 3

Research Questions

The dissertation presented here set out to investigate the processes underlying syntactic and semantic processing in spoken language comprehension in both native and non-native speakers of a language.

The central research questions were:

(1) Can distinct neural correlates be identified to underlie the processing of sentential syntactic and semantic processing in native speakers of a language?

(2) If such a difference can be characterized in one language, does this process necessarily transfer to other languages? In other words, is there cross-linguistic evidence for distinct brain patterns in language processing?

(3) Do native and non-native speakers of a language differ in their language processing strategies on the brain level? If so, does this show domain specificity: In other words does this differ between processing of syntactic and semantic information?

(4) What strategies might non-native speakers of a language use to compensate for deficits in the automaticity of native language comprehension? Is it possible to unify brain imaging data with behavioral data in non-natives to underscore any specific strategy?

Part II

Experiments and Interpretations

Chapter 4

Experiment 1: Syntactic vs. Semantic Processing

4.1 Introduction and Aim

The study presented here used fMRI to distinguish between cerebral areas supporting the processing of sentence-level syntactic and semantic information in native speakers. Electrophysiological studies demonstrated previously that these two information types are processed on distinct timescales (i.e.: Hahne & Friederici, 2002; Friederici, 2002). The present study used a set of sentence materials that had previously been used in a number of ERP studies to identify those brain areas supporting (1) the processing of syntactic information in anomalous sentences as characterized by the ELAN and P600 and (2) the processing of lexical-semantic information in sentences as reflected by the N400. It should be noted again that the timescale captured by ERPs and fMRI are not comparable– ERPs providing a much more refined level of temporal distinction than fMRI. Therefore the current study did not aim to pinpoint the local generators of these ERP components, however it made use of the fact that differences in cerebral activation had previously been identified using ERPs, and therefore sought to identify differences in the overall network underlying syntactic and semantic processing.

4.2 Participants

Eighteen native speakers of German (8 male, 25.5 ± 2.06 yrs.) participated in this experiment after giving informed written consent. No participant had any history of neurological or psychiatric disorders. All participants had normal or corrected to normal vision and were right handed with laterality quotients of 90-100% according to the Edinburgh handedness scale (Oldfield, 1971).

4.3 Methods and Materials

4.3.1 Material

The experimental material consisted of short sentences containing transitive verbs in the imperfect passive form. Participial forms of 96 different transitive verbs, all of which started with the regular German participial morpheme ’ge’, were used to create the experimental sentences. For each participle, three different critical sentences and one filler sentence were constructed (see Table 4.1).

All sentences began with a noun phrase (NP) made up of a definite article (der, die, or das) and an uninflected singular noun. This noun phrase was followed by the imperfect form of the passive auxiliary verb ’werden’. At this point, sentences in all conditions were constructed identically. In the correct sentences, the participal form of a transitive verb directly followed the auxiliary verb, thus completing a short, acceptable sentence in the imperfect passive tense.

In the syntactically incorrect sentences, the auxiliary verb was directly followed by an inflected preposition, which suggests the initiation of a second NP. The presence of a second NP at this position is entirely acceptable in German, thus the preposition alone poses no problem. This preposition must however be followed by the remaining missing elements of the NP, most critically by a noun. Precisely this was violated in the syntactically incorrect sentences: Immediately following the preposition, the sentence final verb participle was presented instead of the necessary noun. This yielded a clear phrase structure violation. The inflected forms of seven prepositions (in, zu, unter, vor, am, bei, für) were used to construct the syntactically incorrect sentences.

Semantically incongruous sentences had the same grammatical form as correct sentences (NP followed by verb phrase consisting of an auxiliary and the participle form of a transitive verb), however the lexical-conceptual meaning of the participle could not be satisfactorily integrated with the preceding sentence context. One final condition, which was not included in the final fMRI analysis, was additionally presented. This condition constituted correct sentences with the form NP, followed by the auxiliary, followed by a completed prepositional phrase (preposition and necessary noun), followed finally by the participle form of the verb. This filler condition served two purposes: First of all it allowed the number of correct and

Table 4.1: Sentence Materials: Examples of the sentence materials (COR = correct sentences, SYN = syntactically violated sentences, SEM = semantically violated sentences, FILLER = long correct filler sentences) presented in German, plus their English translation equivalents. The critical word in each sentence is underlined. English translations maintain their original word order.

	German Sentences	**English Translation Equivalent**
COR	Das Brot wurde gegessen.	*the bread was eaten*
SYN	Das Eis wurde im gegessen.	*the ice-cream was in-the eaten*
SEM	Der Vulkan wurde gegessen.	*the volcano was eaten*
FILLER	Die Pizza wurde im Restaurant gegessen.	*the pizza was in-the restaurant eaten*

incorrect sentences to be balanced. Secondly, it prevented participants from being able to determine the grammaticality of sentences based solely on the presence of a preposition. In other words, the mere presence of a preposition was not sufficient for predicting sentence acceptability.

The sentences were spoken by a trained female native speaker, recorded and digitized, and presented acoustically to the participants.

4.3.2 Procedure

Two differently randomized stimulus sequences were designed for the experiment. The 96 sentences from each of the four conditions were systematically distributed between two lists, so that each verb occurred in only two out of four conditions in the same list. Forty-eight null events, in which no stimulus was presented, were also added to each list. The lists were then pseudo-randomized with the constraints that (a) repetitions of the same participle were separated by at least 20 intervening trials, (b) no more than three consecutive sentences belonged to the same condition, and (c) no more than four consecutive trials contained either correct or incorrect sentences. Furthermore the regularity with which two conditions followed one another was matched for all combinations. The order of stimuli in each of the two randomized stimulus sequences was then reversed, yielding four different lists. These were distributed randomly across participants.

An experimental session consisted of three 11 minute blocks. Blocks consisted of an equal number of trials and a matched number of items from each condition. Each session contained 240 critical trials, made up of 48 items from each of the four experimental conditions plus an equal number of null trials, in which no stimulus was presented and BOLD response was allowed to return to a baseline state.

The 240 presented trials lasted 8 seconds each (i.e., 4 scans of TR=2 s). The onset of each stimulus presentation relative to the beginning of the first of the four scans was randomly varied in four time steps (0, 400, 800, 1200 ms). The purpose of this jitter was to allow for measurements to be taken at numerous time points along the BOLD signal curve, thus providing a higher resolution of the BOLD response (Miezin et al., 2000). After the initial jittering time a fixation cue consisting of an asterisk in the center of the screen was presented for 400 ms before presentation of the sentence began. Immediately after hearing the sentence the asterisk was replaced by three question marks, which cued participants to make a judgment on the correctness of the sentence. Maximal response time allowed was 2000 ms. Identifying the type of error was irrelevant. Participants indicated their response by pressing buttons on a response box. After the response the screen was cleared. Incorrect responses and unanswered trials elicited a visual feedback. These trials, as well as two dummy trials at the beginning of each block, were not included in the data analysis.

4.3.3 fMRI Data Acquisition

Eight axial slices (5mm thickness, 2mm inter-slice distance, FOV 19.2 cm, data matirx of 64 x 64 voxels, in-plane resolution of 3 x 3 mm) were acquired every 2 seconds during functional measurements [BOLD sensitive gradient EPI sequence, TR = 2 seconds, TE = 30 ms, flip angle = 90, acquisition bandwidth = 100 kHz] with a 3 Tesla Bruker Medspec 30/100 system. Prior to functinal imaging T1-weighted MDEFT images (data matrix 256 x 256, TR 1.3 s, TE 10 ms) were obtained with a non-slice-selective inversion pulse follwed by a single excitation of each slice (Norris, 2000). These were used to coregister functional scans with previously obtained high resolution whole head 3D brain schans-128 sagittal slices, 1.5 mm thickness, FOV 25.0 x 25.0 x 19.2 cm data matirx of 256 x 156 voxels (Lee et al., 1995).

4.3.4 Data Analysis

The functional imaging data was processed using the software package LIPSIA (Lohmann et al., 2001). Functional data were corrected first for motion artefacts and then for slicetime acquisition differences using a cubic-spline interpolation. Low-frequency signal changes and baseline-drifts were removed by applying a temporal highpass filter to remove frequencies lower than 1/60 Hz. A spatial filter of 5.65 FWHM was applied.

The anatomical images acquired during the functional session were co-registered to the previously recorded high-resolution EPI-T1 full brain scan and then transformed by linear scaling to a standard size (Talairach & Tournoux, 1988). This linear normalization process was further refined by a subsequent non-linear transformation process, by which linearly transformed images of all participants were matched according to anatomical landmarks to a single anatomical image (Thirion, 1998). The transformation parameters obtained from both normalization steps were subsequently applied to the functional data. Voxel size was interpolated during co-registration from 3 x 3 x 5 mm to 3 x 3 x 3 mm.

The statistical evaluation was based on a least-squares estimation using the general linear model for serially autocorrelated observations (Worsley & Friston, 1995). The design matrix was generated with a synthetic hemodynamic response function and its first and second derivatives (Friston et al., 1998; Josephs et al., 1997). The model equation, made up of the observed data, the design matrix and the error term, was convolved with a Gaussian kernel of dispersion of 4 s FWHM. For each participant two contrast images were generated, which represented the main effects of (1) syntactically violated sentences vs. correct sentences, and (2) semantically violated sentences vs. correct sentences. As noted before, each individual functional dataset was aligned with the standard stereotactic reference space, so that a group analysis based on the contrast-images could be conducted.

The single-participant contrast-images were entered into a second-level random effects analysis for each of the contrasts. The group analysis consisted of a one-sample t-test across the contrast images of all subjects that indicated whether observed differences between conditions were significantly distinct from zero (Holmes and Friston, 1998). Subsequently, t-values were transformed into Z-scores. To protect against false positive activations, only regions with Z-score greater than 3.09 ($p < 0.001$; uncorrected) and with a volume greater than 400 mm^3 (14 measured voxels) were considered. Local maxima were identified within the reported clusters. A voxel was defined to be a local maximum if its z-value exceeded 3.09 and if it was largest within a 5 mm radius.

The mean percent signal change across participants in the maximally activated voxel in group contrasts is depicted in Figure 4.1.

Table 4.2: Performance rates and reaction times for participants listening to correct sentences (COR), syntactically anomalous sentences (SYN) and semantically anomalous sentences (SEM) in their native language.

	Percent Correct ± Std. Error			Reaction Time ± Std. Error		
	COR	SYN	SEM	COR	SYN	SEM
L1	97 ± 0.7	95 ± 0.8	94 ± 1.7	367 ± 19	369 ± 19	401 ± 19

4.4 Results

4.4.1 Behavioral Results

Performance rates and reaction times of participants in the different sentence conditions can be seen in Table 4.2. Reaction times are not a true measure of on-line sentence processing, and will not be discussed further.

Performance rates were subjected to a repeated measures ANOVA with the within subject factor Condition (COR, SYN, SEM). No significant difference between performance in the different experimental conditions could be identified [F(2,34) = 2.42; p = 0.10].

4.4.2 Imaging Results

Coordinates, Z-max values and volume of activated regions can be taken from Table 4.3. Selected activations can be seen in Figure 4.1.

Syntactic processes were investigated in a direct comparison of syntactically violated sentences vs. correct sentences. This comparison showed more activation for syntactic anomalies than for correct sentences within the mid portion of STG (BA22) bilaterally, lateral to Heschl's Gyrus (HG). This activation pattern was stronger and more extended in the left than in the right hemisphere. The activation was seen to extend to more anterior and posterior portions of the supratemporal plane in the left hemisphere: Within the left hemisphere activation two local maxima could be identified, one in the mid portion of STG, directly lateral to HG (-59, -22, 12), and one at a more anterior location (-58, -4, 3) within STG (planum polare). Within the right hemisphere three local maxima were identified, clustering around the mid portion of the STG, lateral to HG.

Correct sentences elicited a greater response than syntactically incorrect sentences primarily in two distinct cortical areas. The first of these activation sites corresponds to an region within left superior frontal gyrus. The second area of interest in this contrast is the

Table 4.3: Talairach coordinates, Z-values and volume of the activated regions for the different contrasts: syntactically anomlaous sentences vs. correct sentences, semantically anomalous sentences vs. correct sentences and correct sentences vs. each anomaly condition. Z-values were thresholded at $Z > 3.09$ ($P < 0.001$, uncorrected) and clusters had a minimum size of 14 voxels ($400mm^3$).

	x	y	z	Z-max	Volume	Region
				Native Speakers of German		
SYN-COR	-59	-22	12	4.81	2919	L. Mid STG
	56	-19	6	4.55	835	R. Mid STG
COR-SYN	-13	41	15	3.61	1042	L. Superior Frontal Gyrus
	-5	-43	38	3.71	541	L. Posterior Cingulate
	-7	-46	24	3.77	561	L. Posterior Cingulate
SEM-COR	-40	23	3	5.33	6082	L. IFG (BA45/47)
	41	14	18	4.3	657	R. IFG (BA44/6)
	-55	-52	12	4.01	448	L. Posterior MTG
COR-SEM	4	-58	47	3.76	878	R. Precuneus
	1	-43	30	4.23	4026	R. Posterior Cingulate

left posterior cingulate gyrus. Within left posterior cingulate cortex two clusters of increased activation in response to correct sentences were observed. Analysis of timecourse data collected from posterior cingulate cortex revealed that activation in this region was not a reflection of increase in signal change in response to correct sentences, but rather reflected a decrease in signal change intensity in response to the anomalous condition.

Semantic processes were investigated in a direct comparison of semantically anomalous sentences vs. correct sentences. This comparison revealed greater levels of activation in the IFG, bilaterally in response to semantic anomalies. Again, this pattern of activation was more pronounced in the left than in the right hemisphere. In left IFG the activation included BA44,45,47, whereas the activation in the right hemisphere was restricted to the area surrounding the junction of precentral sulcus and inferior frontal sulcus (BA44/6). A further region of increased activation in response to semantic anomalies was observed in left posterior STS/MTG.

Correct sentences elicited a greater response than semantically anomalous sentences in two posterior medial areas, namely (1) a region within the right precuneus, and (2) a region within right posterior cingulate cortex. As in the case of the direct contrasts between syntactic anomalies and correct sentences, timecourse data showed that posterior cingulate

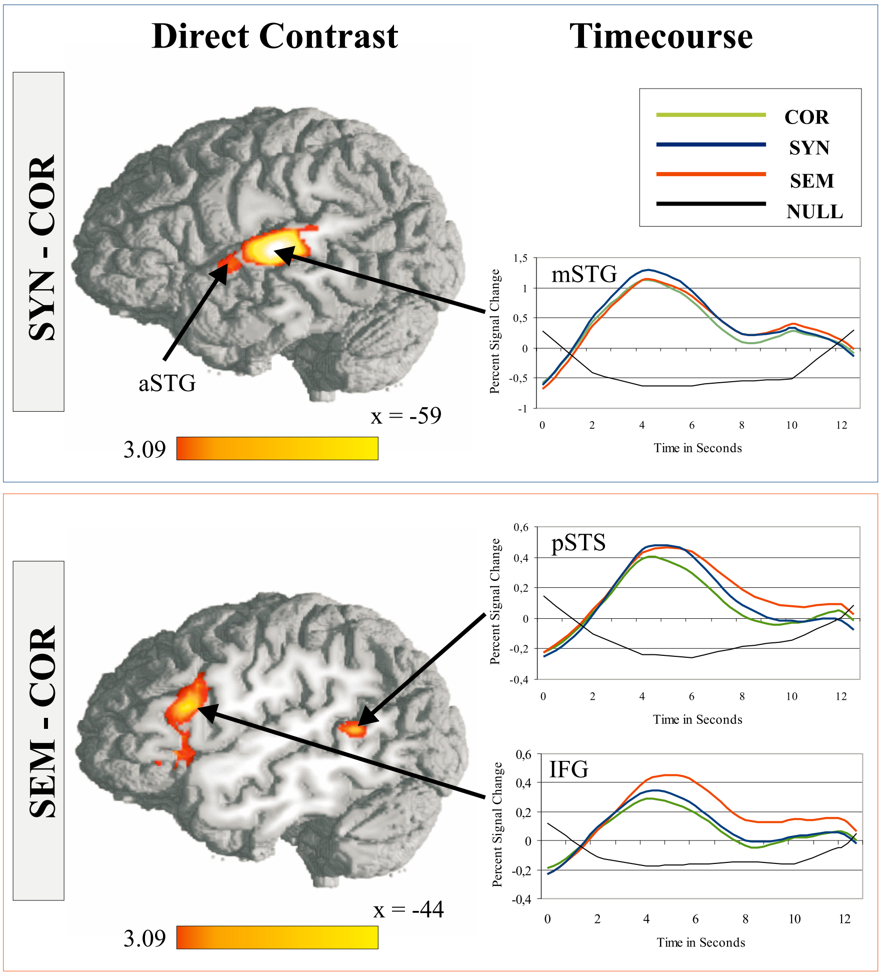

Figure 4.1: Direct contrast images showing differences in activation between (1) syntactically incorrect and correct sentences (SYN - COR), and (2) semantically incorrect and correct sentences (SEM - COR) In the direct contrast SYN - COR, increased activation is seen in response to SYN in the superior temporal gyrus both in a more anterior region (aSTG) and a mid lateral region (mSTG). In the contrast SEM - COR, increased activation is seen in response to SEM in the left inferior frontal gyrus (IFG) and posterior superior temporal sulcus (pSTS).

activation reflected less an increase in signal change in response to correct sentences than a decrease in signal change in correlation with anomalous sentences.

4.5 Discussion

Experiment 1 was conducted in order to identify neural correlates of sentential syntactic and semantic processing in native speakers. Syntactic and semantic processing were dissociated from one another by way of a violation paradigm. By comparing the brain's response to sentences containing a syntactic anomaly vs. well-formed sentences, cerebral regions supporting syntactic processing were identified. Likewise, regions supporting semantic processing were captured in a direct comparison between the brain's response to sentences containing semantic anomalies vs. correct sentences. The results show different cerebral regions to be involved in the processing of syntactic and semantic information. In the following paragraphs these differences will be discussed against the background of already existing neuroimaging literature.

It should be noted that a different analysis of these same results has already been published (Friederici et al., 2003). In this paper we analyzed differences between conditions using only the ROI analysis method. In other words, no direct contrasts were reported. Here the results of this study were reanalyzed using direct contrasts in order to improve the comparability of results to the following studies. All of the areas observed activated in the direct contrast analysis were also observed in the ROI analysis.

4.5.1 Syntax

Syntactically anomalous sentences elicited more activation than correct sentences in native speakers within the bilateral STG. This activation was clearly left lateralized, and centered in the left hemisphere around two neighboring foci: One anterior to Heschl's Gyrus (HG) in the planum polare, and one in mid STG (mSTG), lateral to HG (see Table 4.3 and Figure 4.1).

Anterior STG (aSTG) has been cited in other studies examining on-line syntactic phrase structure building during auditory sentence comprehension (Bavelier et al., 1997; Friederici et al., 2000a, 2003; Humphries et al., 2001; Meyer et al., 2000), as well as patient studies investigating the processing of morphosyntactic information (Dronkers et al., 1992, 2004). On the basis of these and other data, it has been suggested that a highly automatized local structure building process is supported by this region (Friederici et al., 2000a, 2003). Specifically, aSTG has been suggested to support comprehension of sub-sentential constituent structures (Dronkers et al., 2004). In Experiment 1 syntactically anomalous sentence structures draw on local structure building processes above and beyond that required by correct sentences due to the presentation of the prepositional head. Increased activation in aSTG is proposed to reflect problems in integrating the incongruent sentence final word into the initiated prepositional phrase. The anterior STG activation is thus suggested to reflect the detection of a phrase structure incongruency based on word category (morphosyntactic) information.

Anterior STG/STS (aSTG/aSTS) has also been implicated in the mapping of sound onto meaning in speech perception (Scott et al., 2000; Scott, 2004). Specifically, two functional pathways originating in primary auditory cortex (PAC) and progressing in opposite directions along the lateral temporal plane have been suggested to support different aspects of speech processing (Scott et al., 2000; Scott & Johnsrude, 2003,). The first of these, the anterior stream, progresses from PAC to aSTG/aSTS, and has been implicated in the comprehension of intelligible speech, even if the acoustic parameters of speech stimuli have been so altered as to make stimuli distinct from natural speech (Scott et al., 2000). It is not clear why phrase structure violations should elicit more activation than congruent sentences in areas responsible for mapping sound onto meaning, as both incongruent and congruent sentence materials were 'intelligible' in the sense proposed by Scott and colleagues. However, although the site of activation reported in Experiment 1 lies within aSTG, it does not extend to aSTS, as seen in the studies by Scott and colleagues. The two results are difficult to compare, as Scott and colleagues used PET, which for technical reasons provides a better signal in anterior STS than fMRI.

The second peak of activation observed in Experiment 1 is located in mid-lateral STG (mSTG). The precise role of the mSTG activation is unclear, as its proximity to primary auditory cortex makes it a likely candidate for auditory processing in general, and not a specific correlate of phrase structure processing. This is particularly the case as the syntactically violated sentences in this study were created by inserting an incomplete prepositional phrase (PP) into an otherwise coherent sentence. Syntactically anomalous sentences were therefore always one word longer than correct sentences (see examples in Table 4.1). It is known that increased time spent on completing a given task brings on greater levels of activation in neuroimaging studies (Poldrack, 2000). Along these same lines, it has been reported that an increasing amount of auditory input is correlated with increased activation in the STG (Binder & Price, 2001). Therefore increased activation within mSTG may simply reflect additional auditory processing of the extra word in syntactically anomalous sentences.

Initial support for this idea comes from a post-hoc analysis of the brain's response to the filler sentences presented in Experiment 1. These sentences were presented in order to prevent participants from making sentence judgments based on the mere presence of a preposition. Because filler sentences contained a competed prepositional phrase, they were clearly longer than simple correct sentences (see examples in Table 4.1). In a direct comparison between the brain's response to filler vs. correct sentences, increased activation is observed for the longer sentence condition in bilateral mSTG. Although at first glance this appears to be good evidence for the additional-acoustic-input-hypothesis, the possibility that the mSTG is involved in the creation of phrase structure expectancies can nevertheless not be excluded: In both the filler and the syntactically anomalous sentence conditions the head of an additional phrase (the preposition) is presented, and participants may in both cases have constructed phrase structure expectancies above and beyond those necessary for the parsing of simple correct sentences.

Further evidence that the mSTG activation is indeed an indication of processing above and beyond additional acoustic input comes from a further study not presented here, in which we presented native speakers with written sentences containing phrase structure violations (Rüschemeyer & Friederici, submitted). In this study, native speakers show comparable mSTG activation in response to phrase structure violations, although this is in no way attached to a greater amount of acoustic stimulation. Therefore, while some portion of mSTG activation in response to syntactically anomalous sentences may be a reflection of longer sentence presentation, it seems that additional acoustic input cannot account for this activation alone.

4.5.2 Semantics

The most robust site of increased activation for sentences containing a semantic violation in comparison to correct sentences could be seen in the left IFG. This observation is in holding with numerous studies investigating various aspects of semantic processing, and specifically strategic semantic retrieval (Cabeza & Nyberg, 2000; Dapretto & Bookheimer, 1999; Thompson-Schill et al., 1997; Wagner et al., 2001). In particular, the inferior portion of IFG (BA47) has been suggested to play a role in processing semantic relationships between words or phrases, or in selecting a word based on semantic features from among competing alternatives (Bookheimer, 2002; Poldrack et al., 1999). In the current study, participants faced with a semantically implausible word in a sentence experience difficulties in establishing a sensible relationship between the anomalous word and the previous sentence context, resulting in increased levels of activation within inferior IFG. Importantly such activation has nothing to do with long term storage of semantic representations, rather it is thought to reflect a very goal-oriented, strategic process of retrieval (Wagner et al., 2001) or comparison/analysis (Thompson-Schill et al., 1997). It is only in the realization that a given word does not match the participant's expectations that such IFG activation makes sense in relation to semantic processes.

A second area of increased activity in response to semantically anomalous sentences was observed in the left posterior STS/MTG. The domain specificity of this activation (i.e.: the fact that the activation reaches significance in the direct comparison between semantic anomalies and correct sentences, but not between syntactic anomalies and correct sentences) is perhaps misleading, as a small region (28 mm^3) does show substantial differential activation in response to syntactic errors as well. The activity in this region is best characterized in the timelines, seen in Figure 4.1: Here it is evident that the response to both anomalous conditions is quite similar. It is suggested that activation in the posterior STG is a result of the increased effort involved in integrating an anomalous structure into a sentence. This unsuccessful integration process is common to both violation conditions, and simultaneously delineates the processing of both violation types from the processing of correct sentences. It is proposed that pSTG supports a processing stage during which different types of information, e.g. semantic, syntactic and pragmatic information are mapped onto each other to achieve a final interpretation (see also Friederici & Kotz, 2003). However, as the differential response to semantic anomalies alone reached the double-threshold set to reduce the chance of reporting false positives, further discussion will be restricted to the domain of semantic processing.

As discussed in the Section 4.5.1, the functionality of regions within STG remains an open topic of research. The dual pathway model proposed by Scott and colleagues (see previous section) suggests anterior and posterior pathways, both originating in primary auditory cortex (PAC) to support speech processing (Scott, 2004). While the anterior pathway is proposed to support the processing of intelligible speech, the posterior pathway (running from PAC to the temporo-parietal junction area via pSTG/pSTS) is suggested to be involved in the mapping of speech sounds onto motor representations of articulation. In this model, the STS is proposed to aid in accessing mental representations of the sound structure of word forms (Scott, 2004). A slightly elaborated rendition of the functionality of the posterior pathway is proposed by Hickok & Poeppel (Hickok & Poeppel, 2000, 2004). Specifically, the authors propose the existence of (1) a ventral stream, originating in pSTG, and projecting ventro-laterally toward inferior posterior temporal cortex, serving the interface between sound-based representations of speech (contained in STG) and conceptual representations (widely distributed in the cortex); and (2) a dorsal stream, projecting through parietal cortex to frontal regions and supporting the interface between perceptual and motor representations of speech.

Because further areas implicated in the projections proposed by Hickok & Poeppel were not captured in the eight slices acquired in Experiment 1, it is impossible to do more than speculate on whether or not semantic anomalies may indeed have made use of the ventral projection proposed in the dual pathways model. However, it is possible that pSTG activation in response to semantic anomalies reflects processing along the ventral stream, which is suggested to subserve the mapping of acoustically represented word forms onto conceptual meaning. In the face of a semantic incongruency, a more intensive search for a congruent semantic representation of the incongruent word may have been instigated, eliciting more activation in pSTG as well as in inferior temporal cortex. Inferior temporal lobe was, unfortunately, not captured in the eight slices acquired in Experiment 1.

4.6 Conclusion

In this first experiment different brain regions were identified to be involved in the processing of syntactic and semantic violations in spoken sentences. While the processing of all language stimuli most certainly involves various portions of a fronto-temporal network, specific areas within the language network could be identified to be more sensitive to processing within a specific linguistic domain (i.e.: syntax or semantics). Along these lines, it should be explicitly stated that all activated regions discussed here were captured in direct contrasts between brain activation related to processing sentences containing a specific violation vs. sentences containing no violation. The comprehension of a correct sentence clearly relies on successful processing of syntactic and semantic information as well. This may seem trivial, but is important to keep in mind, as any areas commonly involved in the processing of correct and violated sentences are not captured in this analysis. Therefore the regions of increased activation discussed here point to brain regions responding to incompatible sentence stimuli specifically. The regions discussed are therefore not exhaustive, but should be thought of as important points within a greater whole.

That stated, the detection of syntactic anomalies brought on increased activation in several regions within the STG. STG activation is proposed to underlie on-line phrase structure building processes on the basis of functional elements (i.e.: function words and morphosyntactic information). The detection of semantic anomalies most reliably activated the IFG. Although this activation was bilateral, there was a clearly greater involvement of left hemisphere than right hemisphere. It is suggested based on the existing literature that this activation reflects increased difficulties in determining the semantic relationship between the anomalous sentence-final word and the rest of the sentence. A further area of increased activation correlating with semantic anomalies was observed in the posterior reaches of STS, spreading into MTG. Because there is a tendency towards increased activation in this area in response to syntactic anomalies as well, it is suggested that this region is not domain specific, but rather plays a role in the final integration of multiple information sources, e.g. semantics, syntax, pragmatics, etc.

Chapter 5

Experiment 2: Crosslinguistic Study

5.1 Introduction and Aim

The study introduced in this chapter investigated whether or not the results of Experiment 1 (showing unique regions of activation in conjunction with syntactic and semantic processing) can be generalized across languages. To this end, native speakers of two different languages were tested in their respective native language: German sentences were presented to native German participants, and Russian sentence stimuli were presented to a group of native Russian participants. In each case the stimulus materials used elicited reliable effects at the electrophysiological level (Hahne, 2001). Using fMRI we recorded changes in the hemodynamic response of participants to examine which brain regions are involved in sentence processing in two different native languages. Given the similar ERP patterns seen in native speakers of different languages in response to language stimuli in their native language, we expected to see similar brain regions activated in the processing of different languages by native speakers.

5.2 Participants

Eighteen native speakers of German and seven native speakers of Russian (3 male, aged 23 to 32, mean age 30.5 years) participated in the study after giving informed consent. The results of the original group of German participants are reported in Chapter 4. In order to make the groups of native speakers in the current study more comparable in terms of size, we randomly selected 7 German native speakers from the original 18 to subject to further analysis. The Russian native speakers investigated in this study were second language learners of German,

Table 5.1: Sentence Materials: Examples of the sentence materials (COR = correct sentences, SYN = syntactically violated sentences, SEM = semantically violated sentences) presented in German and Russian, plus their English translation equivalents. The critical word in each sentence is underlined. English translations maintain their original word order.

	German	**Russian**
COR	Das Brot wurde gegessen.	Ja dumaju, chto produkty prinesut.
	the bread was eaten	*I think that the food is brought*
SYN	Das Eis wurde im gegessen.	Ja dumaju, chto ovoschi dlya prinesut.
	the ice-cream was in-the eaten	*I think that the vegetables for-the are brought*
SEM	Der Vulkan wurde gegessen.	Ja dumaju, chto grom prinesut.
	the volcano was eaten	*I think that the thunder is brought*
FILLER	Die Pizza wurde gegessen.	Ja dumaju, chto pripravy dlya borsht prinesut.
	the pizza was in-the eaten	I think that the spices for-the soup are brought

and had been living in Germany for an average of 7 years. No participant had any history of neurological or psychiatric disorders. All participants had normal or corrected to normal vision, and were right handed (laterality quotients of 90 to 100 according to the Edinburgh handedness scale) (Oldfield, 1971).

5.3 Methods and Materials

5.3.1 Material: German

The same set of materials as used in Experiment 1 was used in this study (see Table 5.1).

5.3.2 Material: Russian

Russian sentences were used that are as similar as possible in terms of their syntactic structure to the German sentences described in the last chapter (see Table 5.1). This required us to take into consideration a number of features that are specific to the Russian language and could potentially increase variability in the experimental sentences. These constraints are listed here:

(a) Many Russian prepositions are homonymous to verb prefixes. This may render the targeted syntactic violation ambiguous, because in acoustically presented stimuli, the prepositions may be interpreted as verb prefixes and, therefore, may be taken as legal continuations of the sentence. Only later, when a mismatch between the prefix and the verb occurs, can a violation be detected. Such a violation, however would be morphological in nature and, thus, completely different from the intended syntactic violation. In order to avoid this ambiguity, we attempted to use prepositions that never occur as verb prefixes. However, pilot studies revealed that some of these prepositions, namely cherez (spatially: through, over; temporally: in), okolo (by, next to), pered (spatially: in front of; temporally: before), and vozle (by, next to) failed to the ERP patterns typical for syntactic violations. Only the preposition dlya (for) was suitable to create syntactic violations, so this preposition was used for the entire set of stimulus materials.

(b) For the semantic and syntactic violation to occupy identical positions, the main verb had to be sentence-final. This allowed us to keep word order as similar as possible across all sentence types. Moreover, in order to minimize differences in the prosodic contour, the sentence-final verb received stress in all sentences. Russian permits considerable freedom in word order, and stress is used to indicate the focus of the sentence. Sentence-final stress indicates either contrastive or non-contrastive focus on the verb, while stress elsewhere always indicates contrastive focus. Thus, sentence-final stress was the only possibility to keep the sentences identical with respect to prosodic contour and informational structure. It also eliminated any early prosodic cues that would give away the upcoming sentence structure. Care was taken to ensure that the minimal focus on the verb imposed by sentence-final stress would not conflict with the meaning of the whole sentence.

(c) Russian verbs can be either intransitive (unaccusative or unergative) or passivized transitive. It was necessary to use both verb types, because it proved impossible to find 160 different subjects of intransitive verbs. However, the factor of verb type was counterbalanced by constructing half of the sentences with intransitive verbs and half with passivized transitive verbs.

(d) These unavoidable differences in verb type resulted in different syntactic functions of the NP. In sentences with intransitive verbs, the NP was the subject of the sentence. In sentences with passivized transitive verbs, the NP was the object of the sentence. (Note that Russian permits null-subject sentences.) In Russian, the syntactic function of an NP can also be marked by its morphological case. Nominative case marks the subject and accusative case marks the object of a sentence. However, nominative-accusative marking is often neutralized in Russian nouns, so that the morphological structure of the noun sometimes provides unambiguous information about the function of the NP and sometimes not. Specifically, regular feminine singular and animate masculine singular nouns provide unambiguous subject and object marking. All other nouns (inanimate masculine, irregular feminine, neuter and plural) do not. In order to control for case-marking ambiguity, feminine and masculine animate nouns were avoided. Thus, the NP was always morphologically ambiguous with respect to case marking, and only the verb indicated whether the NP was subject or object of the sentence.

(e) In order to avoid confounds associated with coarticulation and prosodic cues on the preposition dlya, all sentences in the 'syntactic violation' condition were recorded inserting bi-syllabic non-words after the preposition. The non-words were composed of the first syllable of the upcoming verb and the preposition dlya. For example, the sentence Ja nadjus', chto polotence dlya vysochnet. (I hope that the towel for will dry.), which contains a syntactic violation, was recorded as Ja nadjus', chto polotence dlya vydlja vysochnet. During recording, the speaker attempted to produce a prosodic pattern of the sentence such as if the non-word vydlja was a noun. All sentences were subsequently digitized, and the non-word was deleted out of the sentences containing a syntactic violation. The spliced sentences do not sound acoustically unusual to native speakers. Using the abovementioned constraints, a total of 160 sentences with 40 sentences in each condition were constructed.

5.3.3 Experimental Procedure: German

The experimental procedure was identical to that described in Chapter 4.

5.3.4 Experimental Procedure: Russian

Two differently randomized stimulus sequences were designed for Russian sentences. The 40 sentences from each condition were pseudo-randomized with the constraints that (a) repetitions of a participle and null-events never occurred, (b) no more than three consecutive sentences belonged to the same condition, and (c) no more than four consecutive trials contained either correct or incorrect sentences. The regularity with which two conditions followed one another was matched for all combinations. The order of stimulus in each of the two randomized stimulus sequences was reversed, yielding four different lists. These were distributed randomly across participants.

An experimental session consisted of three 11-minute blocks. Blocks consisted of an equal number of trials and a matched number of items from each condition. Each session contained 200 critical trials, made up of 40 items from each of the four experimental conditions plus an equal number of null trials, in which no stimulus was presented.

The 200 presented trials lasted 10 seconds each (i.e.: 5 scans of TR= 2 s). Trials were made two seconds longer in comparison to the German sentences in order to better allow the BOLD response to return to baseline. The onset of each stimulus presentation relative to the beginning of the first of the five scans was randomly varied between 0, 500, 1000 or 1500 ms. Again, this parameter differs from that used for the presentation of German sentences, where a jitter of 0, 400, 800 or 1200 ms was used. We determined 500 ms to be a more intuitively logical jittering step, but do not anticipate that this causes any great difference in the data obtained for Germans and Russians. The presentation procedure was in all other respects identical to that for German sentences.

5.3.5 FMRI Data Acquisition

In the first group of German native participants, 8 axial slices (5mm thickness, 2 mm interslice distance, FOV 19.2 cm, data matrix of 64 x 64 voxels, in-plane resolution of 3 mm x 3 mm) were acquired every 2 seconds during functional measurements (BOLD sensitive gradient EPI sequence, TR=2 s, TE = 30 ms, flip angle 90 degrees, acquisition bandwidth 100 kHz) with a 3 Tesla Bruker Medspec 30/100 system. In the group of Russian native speakers 10 axial slices of the same dimensions were obtained. Prior to functional imaging, T1-weighted MDEFT images (data matrix 256x256, TR 1.3 s, TE 10 ms) were obtained with a non slice-selective inversion pulse followed by a single excitation of each slice (Norris, 2000). These were used to co-register functional scans with previously obtained high-resolution whole-head 3D brain scans (128 sagittal slices, 1.5 mm thickness, FOV 25.0 x 25.0 x 19.2 cm, data matrix of 256 x 256 voxels) (Lee et al., 1995).

5.3.6 Data Analysis

The functional imaging data processing was performed using the software package LIPSIA (Lohmann et al., 2001). Functional data were corrected first for motion artefacts and then for slicetime acquisition differences using sinc-interpolation. Low frequency signal changes and baseline-drifts were removed by applying a temporal highpass filter to remove frequencies lower than 1/60 Hz. A spatial filter of 5.65 mm FWHM was applied. The anatomical images acquired during the functional session were co-registered with the high resolution full-brain scan and then transformed by linear scaling to a standard size (Talairach & Tournoux, 1988). This linear normalization process was improved by a subsequent processing step that performed an additional nonlinear normalization (Thirion, 1998). The transformation parameters obtained from both normalization steps were subsequently applied to the preprocessed functional images. Voxel size was interpolated during co-registration from 3 x 3 x 5 mm^3 to 3 x 3 x 3 mm^3. The statistical evaluation was based on a least-squares estimation using the general linear model for serially autocorrelated observations (Worsley & Friston, 1995).

The design matrix was generated with a synthetic hemodynamic response function (Friston et al., 1998; Josephs et al., 1997). The model equation, made up of the observed data, the design matrix and the error term, was convolved with a Gaussian kernel of dispersion of 4 s FWHM. For each participant two contrast images were generated, which represented the main effects of (1) syntactically violated sentences vs. correct sentences, and (2) semantically violated sentences vs. correct sentences. The group analysis consisted of a one-sample t-test across the contrast images of all subjects, that indicated whether observed differences between conditions were significantly distinct from zero. Subsequently, t-values were transformed into Z-scores. The resulting t-statistics were transformed to standard normalized distribution. Group statistical parametric maps (SPM$\{Z\}$) were thresholded at $Z > 2.57$, ($p < 0.005$, uncorrected). Only clusters of at least 14 connected voxels (i.e., 400 mm^3) are reported.

Penetrance maps evaluating the consistency of group results across participants were calculated as outlined by Fox and colleagues (Fox et al., 1996). Z-images from each participant, characterizing differences in activation between (1) syntactic errors and correct sentences, and (2) semantic errors and correct sentences, were converted to binary images (each voxel valued at either 0 or 1), based on a z-threshold of $p < 0.1$. The binary images were then summed across the seven participants. Resulting maps are color-coded representations of the number of participants showing significant differences in activation in each voxel.

5.4 Results

5.4.1 Behavioral Results

Performance rates and reaction times of participants in the different sentence conditions can be seen in Table 5.2. Reaction times are not a true measure of on-line sentence processing, and will not be discussed further.

Performance rates were subjected to a repeated measures ANOVA with the between subjects factor Group (German, Russian) and the within subjects factor Condition (COR, SYN, SEM). The results yielded no significant main effects [Group: $F(1,12) < 1$; $p = 0.36$; Condition: $F(2,24) = 1.27$; $p = 0.2$] and no interaction between Group and Condition [$F(2,24) = 1.38$; $p = 0.2$] (see Table 5.2).

Table 5.2: Performance rates and reaction times for participants listening to correct sentences (COR), syntactically anomalous sentences (SYN) and semantically anomalous sentences (SEM) in their native language.

	Percent Correct ± Std. Error			Reaction Time ± Std. Error		
	COR	SYN	SEM	COR	SYN	SEM
German	97 ± 1.0	97 ± 1.3	92 ± 3.7	417 ± 34	418 ± 33	449 ± 36
Russian	92 ± 1.6	94 ± 1.7	93 ± 2.3	417 ± 43	394 ± 43	406 ± 53

5.4.2 Imaging Results

Talairach coordinates for the activations discussed here can be found in Table 5.3. Images of selected activations, penetrance maps, depicting stability of activations, as well as time-courses showing the percent signal change for each condition over the course of a trial are shown in Figure 5.1.

5.4.2.1 Direct Contrasts

Syntactic processes were investigated in a direct comparison of syntactically violated sentences vs. correct sentences. This comparison showed more activation for syntactic anomalies than for correct sentences within the mid portion of STG in each group of participants listening to their respective native language. In both groups this activation was lateral to Heschl's gyrus and extended into cortex slightly anterior to the primary auditory cortex. Greater activation levels were observed for correct sentences in comparison to syntactically anomalous sentences in the posterior cingulate and inferior precuneus region. Posterior cingulate activation was observed for correct sentences in both groups of participants. Analysis of the timcourses obtained from this region, however, showed that activation differences were not a reflection of an increase in signal change in response to correct sentences, but rather a decrease in signal change in response to the anomalous condition.

Semantic processes were focused on in a direct comparison of semantically violated sentences vs. correct sentences. This comparison revealed increased levels of activation in IFG in both groups of participants irrespective of native language in response to semantic anomalies. The peak of this activation lay within the pars orbitalis of the IFG (BA45/47) in both groups. Differential activation was again observed in the left posterior cingulate gyrus and precuneus region, with a greater activation level in response to correct sentences as compared to semantically anomalous sentences. As in the comparison with syntactically incorrect sen-

Table 5.3: Talairach coordinates, Z-values and volume of the activated regions for the different contrasts: syntactically anomalous sentences vs. correct sentences, semantically anomlaous sentences vs. correct sentences and correct sentences vs. each anomalous condition. Z-values were thresholded at $Z > 2.57$ ($P < 0.005$) and clusters had a minimum size of 14 voxels (400mm^3).

	x	y	z	Z-max	Volume	Region
				German Native Speakers		
SYN-COR	-56	-19	12	3.90	752	L. STG, maximum and posterior peak
	-55	-5	11	3.55		L. STG, lateral anterior peak
COR-SYN	-43	-58	35	3.11	538	L. Posterior STS, ascending branch
	4	-49	32	2.96	8593	R. Precuneus
SEM-COR	-43	20	6	3.93	1539	L. IFG
COR-SEM	-13	-55	35	3.85	1995	L. Precuneus
	7	-43	21	3.33	426	R. Posterior Cingulate Gyrus
				Russian Native Speakers		
SYN-COR	-47	-28	9	3.81	2091	L. STG, maximum
	-59	-21	12	3.29		L. STG, lateral posterior peak
	-58	-5	8	3.18		L. STG, lateral anterior peak
COR-SYN	-10	-52	30	3.88	6440	L. Precuneus
SEM-COR	-49	26	-6	4.02	822	L. IFG, pars orbitalis (BA 47)
COR-SEM	-4	-43	44	3.40	534	L. Posterior Cingulate

tences, this pattern did not reflect an increase in signal change for the correct condition and is thus not discussed further.

5.4.2.2 Penetrance Maps

Results from the penetrance maps, indicating the number of participants showing significant difference in activation between conditions, show that reported group differences are relatively stable across participants. Maps of all contrasts but one show good consistency between group averages and individual activation patterns.

5.5 Discussion

This experiment was conducted in order to determine whether differences in the cortical representation of syntactic and semantic processing (as observed in Experiment 1) are observed in speakers of two typologically different languages. Specifically, in Experiment 1 a greater involvement of mid to anterior STG in response to phrase structure violations was shown, as well as an increased activation of left IFG in response to semantic anomalies in spoken sentences. The participants in Experiment 1 were native speakers of German, and the sentence materials presented were in German. In the current experiment native speakers of Russian were presented with Russian sentences, which were devised to be as similar as possible to the original German sentences. In other words, sentences in Russian were created which contained comparable anomalies (phrase structure or lexical-semantic) to those presented in Experiment 1.

The results of the study are quite clear cut. Russian native speakers indeed showed comparable activation to German natives when listening to comparable language stimuli in their native language. Phrase structure anomalies brought on increased activation in mid to anterior STG, and lexical semantic anomalies brought on increased activation in left IFG. There was no observable activation in response to either anomaly type in the posterior STS/MTG. It is highly probable that this is a problem of power, as both groups consisted of only seven participants each.

The relevance of these activations will not be discussed further here, as they were discussed in the context of Experiment 1. It suffices to conclude here that native speakers of German and native speakers of Russian confronted with comparable spoken sentence stimuli in their respective native language show comparable patterns of cerebral activation. The

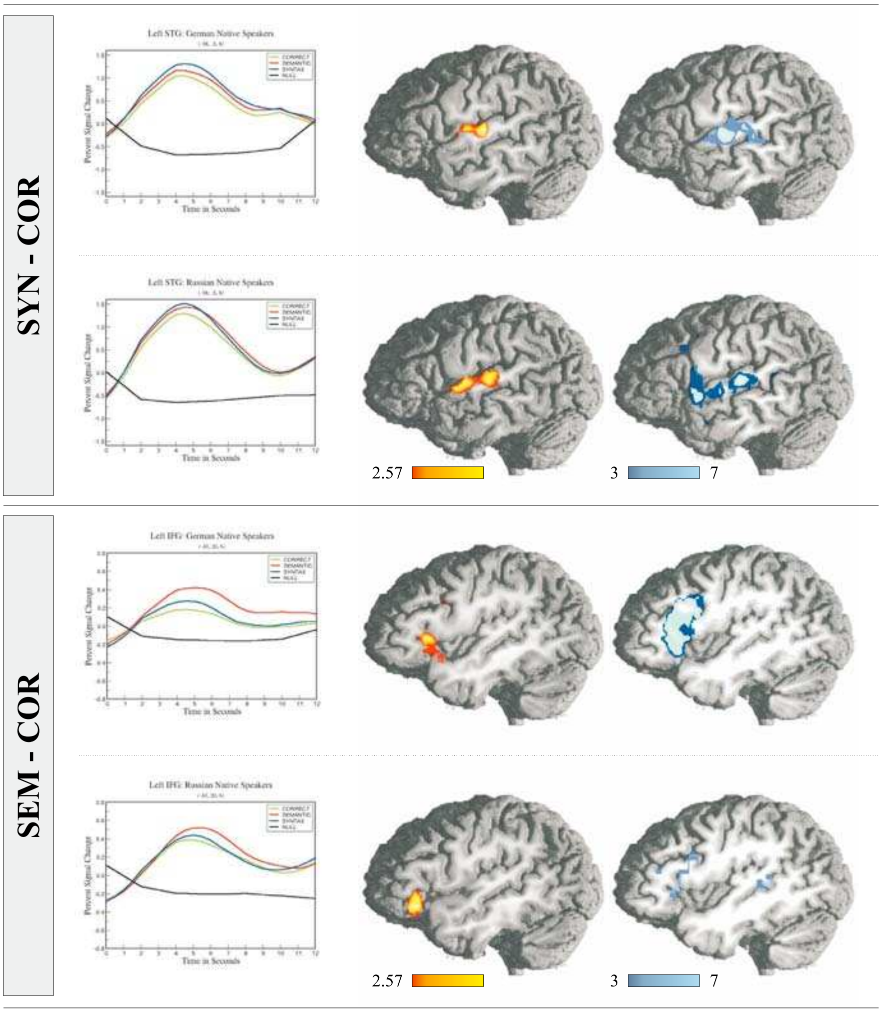

Figure 5.1: Timecourses (showing percent signal change over time), direct contrast images (showing significance levels over each group of participants) and penetrance maps (showing the number of participants with significant activation increase in each voxel) for native speakers of both German and Russian. Values in the direct contrast images, indicated by the color bar, indicate statistical significance. Values in the penetrance maps refer to numbers of individuals. The upper panel depicts those areas showing increased levels of activation for syntactically incorrect sentences (SYN) in comparison to correct sentences (COR). Increased activation levels correlating with syntactic violations are seen in left anterior to mid STG. The lower panel depicts those areas showing increased levels of activation for semantically incorrect sentences (SEM) in comparison to correct sentences (COR). Increased activation correlating with semantic violations is seen in left IFG (BA45/47). Note that percent signal change in STG is greater than in IFG.

results of this experiment show that structurally comparable items in two typologically different languages elicit increased activation in similar brain areas when processed by native speakers. While it would premature to speak of universal language processing areas on the basis of these results alone, such cross-linguistic studies can potentially provide insight as to how strictly organized the biological foundations of language truly are.

5.6 Conclusion

Speakers of two typologically different languages, faced with similar linguistic violations in their respective native language showed engagement of comparable cerebral regions in comprehending spoken language. This indicates that at least those aspects of language processing investigated here are not tied to a specific language, but rather cross-linguistically applicable processes.

Chapter 6

Experiment 3: Processing Native vs. Foreign Language

6.1 Introduction and Aim

This experiment was conducted with the goal of comparing brain activation patterns for native (L1) and non-native (L2) speakers in a sentence comprehension task. Specifically, having seen that native speakers of German and native speakers of Russian show comparable regions of increased activation in response to syntactic and semantic anomalies in their respective native language, the question was asked whether a native speaker of Russian, proficient in German as a second language, would also show comparable activation in response to German sentences. To this end the data obtained for native German speakers in Experiment 1 was compared with results of non-native speakers (Russian natives) listening to the same sentences. Again, electrophysiological results have reliably shown that differences do exist, at least temporally, between the processing of L1 and L2: Early anterior negativities in ERP-responses to word category and morphosyntactic violations are usually absent in non-native speakers, and later integrative components related to semantic and syntactic structure violations typically show both a reduction in amplitude as well as a shift in latency (review see Mueller, in pressa).

6.2 Participants

Eighteen native speakers of German (the same participants from Experiment 1) and 14 non-native speakers of German (3 male, aged 22 to 30, mean age 25.6 years) participated in the study after giving informed consent. Non-native German speakers were native speakers of Russian, and had been living in Germany in for an average of 5 years. Six of the 14 non-native participants were also participants in Experiment 2. No participant had any history of neurological or psychiatric disorders. All participants had normal or corrected to normal vision, and were right handed (laterality quotients of 90 to 100 according to the Edinburgh handedness scale) (Oldfield, 1971).

6.3 Methods and Materials

6.3.1 Material and Experimental Procedure

The same German materials and experimental procedure were used as for the German native speakers in Experiment 1.

6.3.2 fMRI Data Acquisition and Analysis

The data was obtained in an identical manner (i.e.: same scanner and identical parameters were used) to the German natives from Experiment 1.

A within-group analysis of each participant group was made in an identical manner to that described in Experiment 1. Statistical parametric maps were thresholded at $Z > 3.09$ ($p < 0.001$, uncorrected). Only clusters of at least 14 connected voxels (400 mm^3) are reported.

For the between-group comparisons, two-sample t-tests were conducted comparing contrast images from individuals in each group (group of native speakers vs. group of non-native speakers) while listening to each experimental sentence type against a resting baseline. High levels of variance, in particular within the group of non-natives, made the detection of stable effects in the third-level analysis between the two groups of participants more difficult than the direct contrasts observed in the second-level analysis within the groups. Therefore we first of all followed other researchers in lowering threshold levels to $Z > 2.32$ ($p < 0.01$) in determining the significance of between group differences (Perani et al., 1998; Pallier et al., 2003). Furthermore, in order to determine that the size of observed activations was reliably different between groups, we conducted a second third-level analysis based on Bayesian statistics, which provides a probability estimate for the reliability of difference in activation size, expressed as a percentage value between 0 and 100, and is not susceptible to problems of multiple comparisons (Neumann & Lohmann, 2003). To do this, the peak coordinate obtained from the direct contrasts was tested in each group of participants. We report Bayesian statistics for the between-group comparisons only, as we wish to solidify the statistical sig-

Table 6.1: Performance rates and reaction times for native speakers (L1) and non-native speakers (L2) listening to correct sentences (COR), syntactically anomalous sentences (SYN) and semantically anomalous sentences (SEM) in German.

	Percent Correct ± Std. Error			Reaction Time ± Std. Error		
	COR	SYN	SEM	COR	SYN	SEM
L1	97 ± 0.7	95 ± 0.8	94 ± 1.7	367 ± 19	369 ± 19	401 ± 19
L2	85 ± 2.2	76 ± 4.7	86 ± 2.1	478 ± 34	494 ± 47	538 ± 42

nificance of our results in these contrasts. In the within-group contrasts presented in both Experiments 1 and 2, this additional statistical exploration was not necessary.

6.4 Results

6.4.1 Behavioral Results

Performance rates and reaction times of participants in the different sentence conditions can be seen in Table 6.1. Reaction times are not a true measure of on-line sentence processing, and will not be discussed further.

Performance rates were subjected to a repeated measures ANOVAs with the between subjects factor Group (L1, L2) and the within subjects factor Condition (COR, SYN, SEM). A main effect of Group was observed [F(1,30)=25.91; $p < 0.01$] as well as a main effect of Condition [F(2,60)=7.06; $p < 0.01$] and a Group x Condition interaction [F(2,60)= 7.92; $p < 0.01$]. Further analysis revealed (1) a significantly greater percentage of errors for L2 speakers than L1 speakers in all experimental conditions, and (2) only a tendency for differences between conditions within the L1 group [F(2,34)=2.75; $p < 0.1$], but a reliable difference between conditions within the L2 group [F(2,26)=6.84; $p < 0.01$]. Post hoc analysis showed that L2-speakers show a tendency to make more errors in the detection of syntactic errors sentences than in judging correct sentences [F(1,13)=6.27; $p < 0.05$] and are significantly better at detecting semantic anomalies than syntactic anomalies [F(1,13)=9.39; $p < 0.01$]. The level of significance reported is adjusted according to Bonferroni.

6.4.2 Imaging Results

6.4.2.1 Within Group Comparisons

Here we report direct comparisons between each violation condition and correct sentences for non-native speakers of German. The direct contrasts for native speakers of German are not explicitly elaborated upon here, as they were sufficiently discussed in Chapter 4 (Experiment 1). However the coordinates and z-values of local maxima for the group of native speakers is provided for reference in Table 6.2.

In a direct comparison between syntactically anomalous sentences and correct sentences, non-native speakers showed no areas of differential activation. No areas were seen more activated for syntactically anomalous sentences than correct sentences, and likewise no areas were seen to be more involved in the processing of correct vs. syntactically anomalous sentences.

Semantically anomalous sentences, on the other hand, did bring on higher levels of activation when compared to correct sentences, specifically within the left IFG (BA44). This activation spread from superior regions of BA44 into inferior BA45/47. A direct contrast between correct vs. semantically anomalous sentences showed increased levels of activation for correct sentences in right angular gyrus and right posterior STS/MTG.

6.4.2.2 Between Groups Comparisons

In the between-group comparisons the results show those areas that were differentially activated for each group (native speakers or non-native speakers of German) in response to the auditory presentation of well-formed, syntactically anomalous and semantically anomalous German sentences. Talairach coordinates and the probability that the size of activation in a given area is reliably different between the groups based on Bayesian statistics can be found in Tables 6.3 and 6.4. Timecourses, depicting signal change over time and selected direct contrast maps can be seen in Figure 6.2.

6.4.2.3 Direct Contrasts

Non-native Speakers vs. Native Speakers

Non-native speakers showed a different pattern of activation than native speakers in all three experimental conditions. When listening to well-formed, correct German sentences, non-native speakers showed a greater involvement of several cortical and subcortical areas than native German speakers. Cortically, greater levels of increased activation were observed

Table 6.2: Talairach coordinates, Z-values and volume of the activated regions for the different contrasts: syntactically anomlaous sentences vs. correct sentences, semantically anomalous sentences vs. correct sentences and correct sentences vs. each anomaly condition. Z-values were thresholded at Z > 3.09 ($P < 0.001$, uncorrected) and clusters had a minimum size of 14 voxels ($400mm^3$).

	x	y	z	Z-max	Volume	Region
				Native Speakers of German		
SYN-COR	-59	-22	12	4.81	2919	L. Mid STG
	56	-19	6	4.55	835	R. Mid STG
COR-SYN	-13	41	15	3.61	1042	L. Superior Frontal Gyrus
	-5	-43	38	3.71	541	L. Posterior Cingulate
	-7	-46	24	3.77	561	L. Posterior Cingulate
SEM-COR	-40	23	3	5.33	6082	L. IFG (BA45/47)
	41	14	18	4.3	657	R. IFG (BA44/6)
	-55	-52	12	4.01	448	L. Posterior MTG
COR-SEM	4	-58	47	3.76	878	R. Precuneus
	1	-43	30	4.23	4026	R. Posterior Cingulate
				Non-Native Speakers of German		
SYN-COR				no significant differences		
COR-SYN				no significant differences		
SEM-COR	-53	17	21	3.96	696	L. IFG (BA44)
COR-SEM	59	-52	32	3.68	471	R. Angular Gyrus
	50	-52	9	3.61	553	R. Posterior MTG/STS

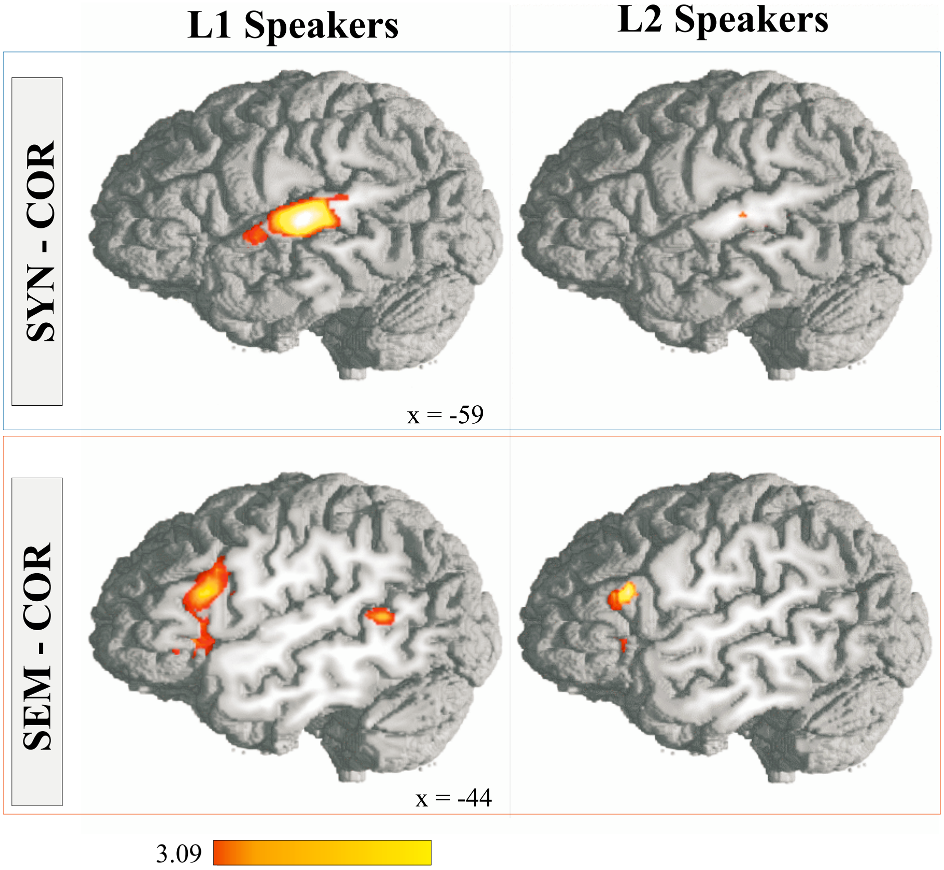

Figure 6.1: Direct contrasts for native (L1, left panel) and non-native (L2, right panel) speakers listening to experimental sentence material in German. The top panel depicts the direct contrast between the BOLD response to syntactically incorrect vs. correct (SYN-COR) sentences. The bottom panel depicts the direct contrast between the BOLD response to semantically incorrect vs. correct (SEM-COR) sentences. Direct contrasts were thresholded at $Z > 3.09$.

for non-native speakers in the left intraparietal sulcus, the left anterior insular cortex and at three points within left frontal cortex. Frontal cortical activation was centered around 3 local maxima located (1) in the superior portion of BA44/6, at the junction point between inferior frontal sulcus and inferior precentral sulcus; (2) in a more inferior portion of BA44; (3) in the left posterior orbital gyrus. On the subcortical level, non-native speakers showed a greater involvement of basal ganglia structures bilaterally, specifically in the head of the caudate nuclei.

When listening to syntactically incorrect sentences, non-native speakers showed a robust area of increased activation in comparison to native speakers in superior posterior reaches of the left IFG (BA44/6), as well as two smaller sites of cortical activation within the left intraparietal sulcus and right angular gyrus. Two further substantial sites of increased activation could be seen subcortically within the caudate nuclei bilaterally.

Semantically anomalous sentences brought on a small cortical activation in the left intraparietal sulcus in non-native speakers as compared to native speakers. Substantial activation could again be observed subcortically in the right and left caudate nuclei.

Native Speakers vs. Non-native Speakers

Native speakers of German, listening to correct sentences in their native language, showed greater levels of activation than non-native speakers listening to the same sentences in the mid portion of the bilateral STG, lateral to Heschl's gyrus, the right parieto-occipital sulcus extending into the precuneus and the right insular cortex.

Syntactically anomalous sentences brought on more activation in native than non-native speakers in the mid portion of the left STG, as well as several cortical sites within the right hemisphere. Right temporal lobe activation was observed in mid portions of STG, homologue to activation seen on the left. Furthermore right posterior STG was shown to be more active in native speakers than non-native speakers. The right posterior insular cortex, right precuneus and right posterior cingulate gyrus also showed increased levels of activation for native speakers than for non-native speakers.

Semantic anomalies brought on increased levels of activation for native speakers in the STG bilaterally. In the left hemisphere this activation was restricted to the mid portions of STG, in the right hemisphere mid and posterior portions of STG/STS were observed to show different levels of activation. Additionally the right anterior and posterior insular cortices, as well as the right parieto-occipital sulcus spreading into precuneus regions, showed more activation in native speakers than in non-natives.

6.5 Discussion

This fMRI study had two aims: (1) To investigate differences in the cortical networks supporting syntactic and semantic information in sentences in non-native speakers of a language, and (2) to investigate differences in the overall cerebral network underlying spoken language comprehension between native and non-native speakers of a language. To this end

Table 6.3: Talairach coordinates, maximum Z-value, volume, and reliability of difference according to Bayes model of the activated regions for the contrasts: non-native speakers (L2) vs. native speakers (L1) listening to correct sentneces; L1 vs. L2 speakers listening to correct sentences. Z-values thresholded at Z > 2.32 (p < 0.01, uncorrected).

	x	y	z	Z-max	Volume	Bayes (%)	Region
Correct Sentences							
L2 > L1	-52	9	24	2.68	119	99.98	L. IFG (BA44/6)
	-49	12	6	3.01	95	99.99	L. IFG (BA44)
	-34	18	-12	2.97	196	99.95	L. Posterior Orbital Gyrus
	-29	18	9	2.72	103	99.82	L. Anterior Insula
	-5	6	3	2.84	207	99.99	L. Caudate Nucleus
	11	15	6	3.22	508	99.99	R. Caudate Nucleus
	-28	-72	41	3.22	281	100	L. Intraparietal Sulcus
L1 > L2	-50	-21	12	3.59	868	99.99	L. STG
	56	-39	12	2.88	206	100	R. STG
	29	-27	0	2.96	149	99.89	R. Temporal Stem
	8	-66	35	3.45	722	100	R. Precuneus
	25	21	12	2.91	512	99.98	R. Anterior Insula
	37	3	-6	3.20	396	99.74	R. Anterior Insula
	32	-33	18	3.38	1446	100	R. Posterior Insula

Table 6.4: Talairach coordinates, maximum Z-value and volume of the activated regions for the contrasts: non-native speakers (L2) vs. native speakers (L1) listening to anomalous sentences; L1 vs. L2 speakers listening to anomalous sentences. Z-values thresholded at Z > 2.32 ($p < 0.01$, uncorrected).

	x	y	z	Z-max	Volume	Bayes (%)	Region
Syntactically Anomalous Sentences							
L2 > L1	-52	9	24	3.16	1104	100	L. IFG
	-28	-72	41	3.34	499	100	L. Intraparietal Sulcus
	34	-57	35	3.44	308	100	R. Angular Gyrus (deep)
	-7	6	3	3.84	2090	100	L. Caudate Nucleus
	8	12	9	3.29	875	99.99	R. Caudate Nucleus
L1 > L2	-53	-18	12	2.75	714	100	L. Mid STG
	49	-12	12	2.48	232	99.99	R. Mid STG
	55	-48	12	2.59	1560	100	R. Post. STG
	32	-33	21	2.49	405	100	R. Post. Insula
	22	-57	24	2.73	1504	99.99	R. Precuneus
	7	-54	15	2.62	299	99.99	R. Post. Cingulate Gyrus
Semantically Anomalous Sentences							
L2 > L1	-20	-78	32	2.91	262	99.99	L. Intraparietal Sulcus
	-5	6	3	3.47	1760	99.99	L. Caudate Nucleus
	11	15	6	3.90	1218	99.99	R. Caudate Nucleus
L1 > L2	-55	-18	9	3.49	762	99.99	L. Mid STG
	52	-12	12	3.08	572	99.99	R. Mid STG
	58	-39	12	2.98	1120	99.99	R. Post. STS
	29	21	6	3.40	485	100	R. Ant. Insula
	35	-33	21	2.77	263	100	R. Post. Insula
	8	-66	35	3.41	489	100	R. Precuneus

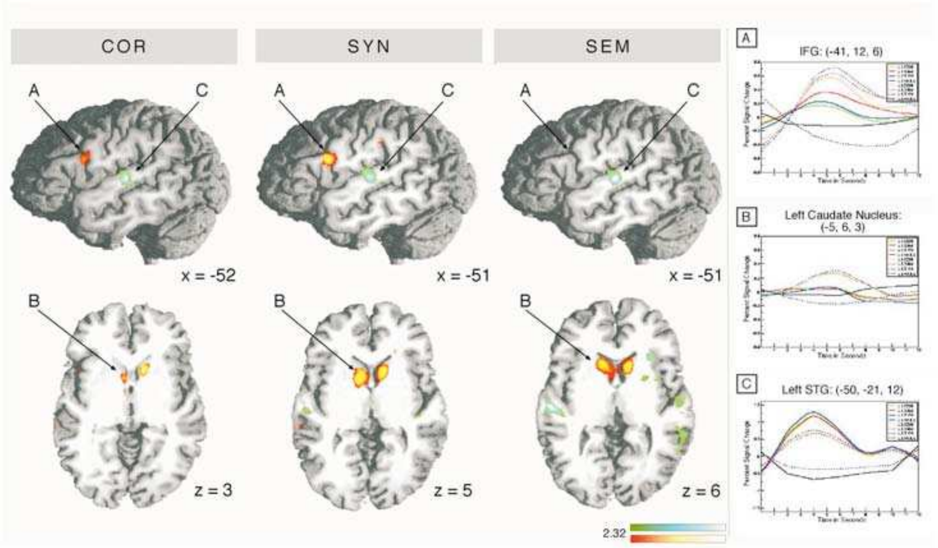

Figure 6.2: Direct contrast maps of native vs. non-native speakers of German listening to correct (COR), semantically anomalous (SEM) and syntactically anomalous (SYN) sentences. Left IFG (A) shows increased activation for non-native speakers of German in all conditions (see timecourses). Due to increased activation of IFG in the SEM condition in native speakers as well, no significant difference is observed in IFG in the direct contrast between native and non-native speakters in the final panel. Bilateral Caudate Nucleus (B) is also activated significantly more by non-native speakers in all conditions. Left STG (C) shows greater levels of activation for native speakers vs. non-native speakers.

the event-related BOLD response of native and non-native German speakers was recorded while participants listened to sentence stimuli in German. Aim 1 was addressed by looking at direct contrasts between experimental conditions in a within-group analysis: Syntactic processing was captured in a direct contrast between those areas showing increased levels of activation for syntactically anomalous sentences in comparison to correct sentences. Semantic processing was captured in a direct contrast between those areas demonstrating increased activation for sentences containing semantic anomalies in comparison to correct sentences. Aim 2 was addressed by looking at between-group differences in response to the various sentence materials.

6.5.1 Syntactic and semantic processing in non-natives

The results of the current study show an interesting dissociation between syntactic and semantic processing in non-native speakers. Specifically, L2 speakers show no regions of significant differential activation in response to syntactically incorrect vs. correct sentences. This is true, although participants were clearly capable of detecting syntactic anomalies (as seen in performance rates). This strongly contrasts the pattern observed in native speakers (results of Experiment 1), which showed a greater involvement of mid to anterior lateral STG in response to the same phrase structure violations. It is important here to keep in mind the nature of the fMRI results presented. First, as always a null result can be the consequence of insufficient power. Future research with additional participants and different paradigms will have to clarify whether the null result obtained in this contrast is reliable. Assuming however, that the result is reliable, the baseline contrast condition used to identify regions of activation responsive to syntactic violations was the BOLD response to correct sentences. Put differently, the null result obtained here shows only that there was no differential response for L2 speakers between parsing correct sentences and parsing syntactically incorrect sentences. There appears to be no *differential* BOLD-response to the initial attempted integration of words into a phrase in non-native speakers. This is in accordance with electrophysiological studies, which have demonstrated that L2 speakers show no initial processing difference for phrase structure compatible and incompatible sentence items (Hahne, 2001; Friederici, 2001; Kubota et al., 2003, 2004). As in these previous studies, the interpretation here is that phrase structure is not violated by incongruous word category in non-natives in the same manner (i.e.: on the same timescale) as in natives. Words belonging to the wrong word category are processed in the same (analytical, explicit) manner as phrase structure compatible words.

In response to semantic anomalies in spoken sentences, non-native speakers showed a reduced, but anatomically comparable area of activation to native speakers. Specifically, L2 speakers showed increased involvement of left IFG. As can be seen in Figure 6.1, the focus of activation in non-native speakers lay further posterior to that observed in natives: Non-natives showed activation predominantly in BA44, while the activation in natives spread to further anterior regions including BA45 and 47. This indicates that non-native speakers process lexical-conceptual information of words in sentences in a manner similar to that demonstrated by natives. The role of left IFG in semantic processing was addressed in Experiment 1. It was pointed out in the discussion to Chapter 4 that left IFG is presumed not to house long-term semantic knowledge (see also Bookheimer, 2002), rather IFG is observed to become additionally engaged in semantic tasks requiring goal-directed, strategic retrieval of conceptual information (Wagner et al., 2001) or direct comparison/analysis (Thompson-Schill et al., 1997). Again, the similarity of the response of native and non-native speakers is in holding with electrophysiological studies, which show a reduced but otherwise comparable response of the brain to semantic anomalies in native and non-native speakers (Hahne, 2001; Weber-Fox & Neville, 1996).

Taken together the results of this study show (1) that non-natives show a differential response to conceptually incompatible words in sentences vs. words which can be easily conceptually integrated. The detection of such semantic violations in sentences appears to rely on similar brain regions to those seen in native speakers. (2) Non-native speakers show no differential response to words belonging to an incompatible vs. a compatible word category in spoken sentences. Such syntactic errors are nevertheless detected, as reflected in the behavioral results. It is suggested that non-native speakers either (1) do not construct phrase structure expectancies, or (2) cannot access word category information quickly enough in order to detect the phrase structure violation. Non-native speakers appear to rely on comparable processing strategies in attempting to integrate phrase structure compatible and incompatible words in sentences.

6.5.2 Language Processing between Native and Non-native Groups

Differences in the overall cerebral network underlying spoken language comprehension between native and non-native speakers of a language were captured in a direct contrast showing between-group differences in response to the various sentence materials. The results showed a general pattern of differential activation across experimental conditions. Specifically non-native speakers showed more activation of frontal cortex and the caudate nucleus bilaterally in response to spoken sentence materials. Native speakers, on the other hand, showed a greater response of left STG.

6.5.2.1 Non-native Speakers

Frontal Cortex

Non-native speakers in the present study, listening to both correct and syntactically anomalous sentence stimuli, show several sites of increased activation in BA44 in comparison to native speakers. The local maximum of one of these activations lies within the superior posterior regions of BA44, along the anterior bank of the inferior precentral sulcus, and is observed in response to both correct and syntactically anomalous sentences. The other lies inferior and anterior to this, also within BA44, and can be seen only in response to correct sentences.

The first of these regions (superior posterior BA44) corresponds to a portion of IFG cited in studies looking at strategic phonological processing (Burton et al., 2000; Poldrack et al., 1999). Importantly, this area does not respond specifically to passive listening (i.e., does not support bottom-up stimulus-driven processes), but rather to strategic processing of auditory input. So, for example, phoneme discrimination tasks elicit increased activation in this area in comparison to pitch discrimination tasks or passive listening to phonemes (Gandour et al., 2002; Zatorre et al., 1996). Burton et al. (2000) argue that phoneme discrimination alone is not enough to elicit pIFG activation, rather tasks requiring segmentation of phonemes coupled with a discrimination task are needed to produce higher levels of activation. It is entirely plausible that non-native speakers experience increased difficulties in recognizing or categorizing acoustically presented phonemes within a speech signal. Behavioral studies seem to support this notion, as they have shown that age of acquisition of a second language influences phonological proficiency, in particular the perception of phonemes in noisy surroundings (Flege et al., 1999; Mayo et al., 1997; Meador et al., 2000). In the current study, highly proficient, but late learners of German were presented with acoustic sentence stimuli in the noisy scanner environment. The increased levels of activation for the non-natives observed in superior posterior IFG could well reflect the increased effort individuals in this group had to invest in order to correctly perceive and categorize the presented speech cues on a purely phonological level. The increased difficulty experienced by non-native speakers in all conditions is characterized by the behavioral results recorded: Non-native speakers made more errors than native speakers in all experimental conditions.

Activation within this portion IFG is different between native and non-native speakers listening to correct and syntactically anomalous sentences, but not to semantically anomalous sentences. The absence of an observable difference between the groups for this condition is caused by the relative increase in IFG activation brought on by semantic anomalies in the group of native speakers (discussed in Chapter 4). This is clear upon inspection of the timecourse information (Figure 6.2).

A second area of interest within BA44 demonstrated greater levels of increased activation in non-native vs. native speakers listening to correct sentence stimuli only. This portion of BA44 corresponds to previously reported findings concerning the processing of syntactic structure (Dapretto & Bookheimer, 1999; Just et al., 1996; Fiebach et al., 2001; Friederici et al., 2000a; Heim et al., 2003). In monolingual studies an increased involvement of this region has been reported for the processing of sentences with increasing syntactic complexity (Caplan et al., 1998, 1999; Caplan, 2001; Just et al., 1996; Stromswold et al., 1996) and for the processing of syntactic transformations in particular (Ben-Shachar et al., 2003). This brain area has also been implicated in the processing of syntactically incorrect sentences, but only when the error was set into focus by the task (Embick et al., 2000; Indefrey et al., 2001; Suzuki & Sakai, 2003). The fact that non-native participants in the current study show more activation than native speakers in this region correlated with correct sentences, suggests that non-native speakers consistently engage more resources in syntactically parsing even simple, correct sentences in their second language. In other words, the lesser proficiency of non-native speakers in their second language causes even simple structures to be parsed as if they were complex. Such an observation is in holding with the failure to observe any difference in the BOLD response of non-native participants to correct vs. syntactically incorrect sentences. Both syntactically correct and incorrect elements in sentences are processed in a similar manner.

Although BA44 is often implicated in the processing of syntactic complexity, it was addressed in Chapter 1 that such studies have often been confounded with short term memory costs. Specifically, it has been argued recently, that transformational processes in parsing sentence structure may rely on working memory, and that IFG activation is actually a reflection of recruitment of this memory system rather than a direct correlate of syntax processing (i.e.: Fiebach et al., 2001, 2002b; Gibson, 1998). IFG has been implicated in studies investigating verbal working memory independent of sentence or syntax processing as well (Smith & Jonides, 1997; Henson, 2001; Xue et al., 2004), providing support for the idea that some aspects of auditory language comprehension may indeed tap into this general cognitive resource. A further possible interpretation of the current results is therefore, that L2 speakers rely to a greater degree on verbal working memory in comprehending spoken sentences. This issue will be addressed at length in Chapter 7.

Caudate Nucleus

Non-native speakers showed increased levels of activation in comparison to native speakers in the subcortical structures of the basal ganglia bilaterally for all sentence stimuli types. Specifically, increased levels of activation were observed in the head of the caudate nuclei in both hemispheres. The role of the basal ganglia in language processing is unclear: Subcortical structures have traditionally been attributed with coordination of movement, while studies looking at cognitive function have tended to concentrate on cortical activation. Therefore, several studies have suggested that basal ganglia activation reflects motor planning in preparation for articulation (Klein et al., 1994, 1995). Along similar lines, it has been suggested that basal ganglia activation supports covert articulatory processes, such as those postulated to underlie covert rehearsal in Baddeley's verbal working memory system (Henson, 2001; Baddeley, 1997).

The indisputably crucial role of the basal ganglia in language processing has recently begun to attract increasing attention (Lieberman, 2002; Watkins et al., 2002; Stowe et al., 2003). Clinical studies have shown that permanent loss of linguistic abilities associated with classic aphasias does not occur in the absence of subcortical damage (Dronkers et al., 1992; D'Esposito & Alexander, 1995; Lieberman, 2002). Furthermore, focal damage to subcortical structures (for example in neurodegenerative illnesses such as Parkinson's disease) results in linguistic and cognitive deficits displaying properties of classic aphasias (Lieberman, 2002) and developmental speech disorders have been shown to correlate with functional and structural abnormalities specifically in the caudate nucleus (Watkins et al., 2002). More recently, a number of ERP studies have shown that focal lesions of the basal ganglia show a selective deficit of controlled syntactic processes as reflected in the P600 (Friederici & Kotz, 2003; Frisch et al., 2003; Kotz et al., 2003). The declarative/procedural model of language processing further predicts a specific role of the basal ganglia in syntactic processing, which is postulated to draw on the procedural memory system in contrast to a knowledge-based episodic memory system (Ullman, 2001b, 2004).

Functionally seen, the caudate nucleus works together with prefrontal cortex in a series of frontocortical loops. Activation of caudate nucleus should thus necessarily be correlated with prefrontal cortex activation. In the current study non-native speakers show increased levels of activation in comparison to native speakers in the head of the caudate nucleus bilaterally, but cortical activation only in left IFG. This is surprising, as functional neuroanatomy indicates that right caudate nucleus activity is necessarily tied to right hemispheric frontal cortical activity.

In light of this fact we looked at the zmaps for each individual participant and plotted local maxima within the left and right frontal cortices (see Figure 6.3). The pattern of distribution seems to be such that local maxima between subjects cluster around two areas within left IFG, corresponding roughly with those areas reported in the direct comparison of native and non-native speakers. However, in the right hemisphere, although most participants do show activation within prefrontal cortex (only two out of fourteen participants show no local maximum in this region), the pattern of distribution is much more variable. In other words, while left hemispheric IFG activation seems to be centered around two distinct foci, right hemispheric activation is present but quite dispersed. In evaluating group statistics, this can have a major effect. While most participants show activations in the same areas within left IFG, activations, although present, do not overlap in right IFG. This leads to a reliable effect in left hemisphere, and no reliable effect in the right hemisphere. As the caudate nucleus is an anatomically much more restricted region, the chance that activation within caudate nucleus overlaps between participants is far greater than in frontal cortex. We postulate that non-native speakers thus show increased levels of activation in comparison to native speakers in left frontal language areas, and in homologous areas within the right hemisphere. However, right hemispheric activations are more widely dispersed and thus less robust in a group statistical analysis. The combination of caudate nucleus activation together with IFG activation is reminiscent of studies investigating verbal working memory (Henson, 2001; Smith & Jonides, 1997; Xue et al., 2004).

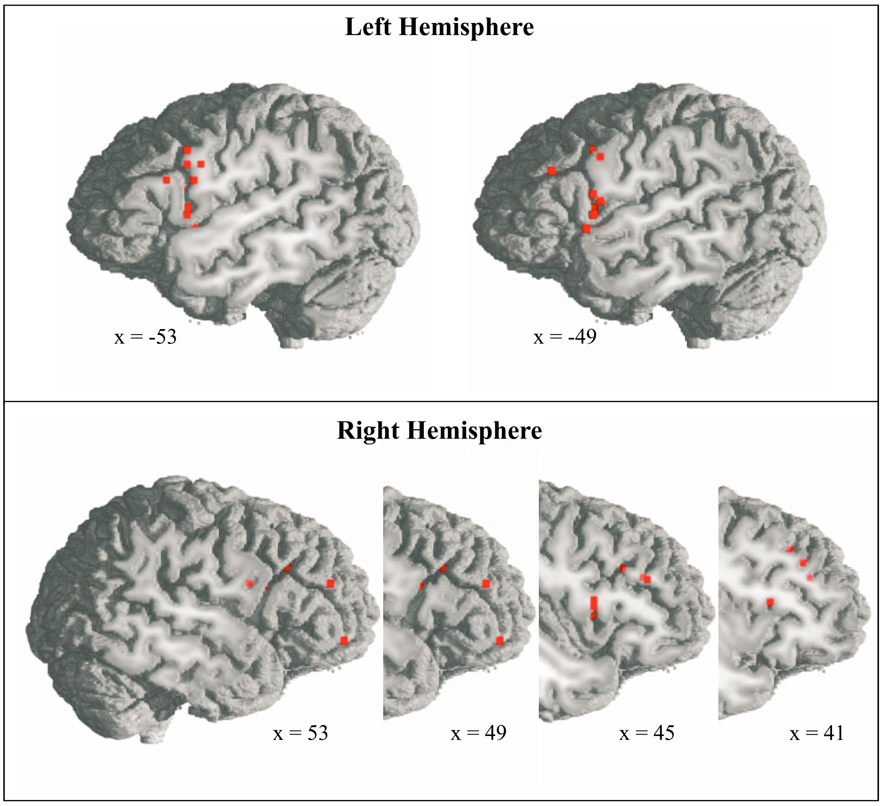

Figure 6.3: Local maxima for individual participants within IFG in the left and right hemispheres. A clustering of activations around 2 local foci can be seen in the left hemisphere (top panel). Local maxima in the right hemisphere (bottom panel) are more dispersed.

6.5.2.2 Native Speakers

Superior Temporal Gyrus

Native speakers of German showed a greater involvement of temporal lobe areas than non-native speakers when listening to all sentence types in German. Specifically, native speakers showed an area of increased activation in central portions of the STG, lateral to Heschl's gyrus (see Figure 6.2). STG and auditory association cortex clearly play a role in the processing of spoken speech, as in all auditory signals, however a functional breakdown of regions within STG in relation to language processing has not yet been clearly determined. It has been argued that anterior and posterior regions of STG process speech signals specifically (Giraud & Price, 2001; Scott & Johnsrude, 2003; Scott et al., 2000). Anterior portions of STG have been suggested to support very specific, semantically driven aspects of lexical retrieval (Binder & Price, 2001; Kiehl et al., 2002) and also syntactically motivated phrase structure building process (Friederici et al., 2000a, 2003; Humphries et al., 2001; Meyer et al., 2000), whereas posterior STG has been suggested to support general sentential evaluation and integration (Friederici et al., 2003).

In Experiment 1 and Experiment 2 increased levels of activation were observed in native speakers in mid to anterior STG in response to sentences containing a phrase structure violation. Despite the spatial proximity of mSTG to primary auditory cortex, it was reasoned on the basis of preliminary results from a visual language experiment (Rüschemeyer & Friederici, submitted) that this activation is not a reflection of mere acoustic processing. The fact that native speakers show higher levels of activation in mSTG than non-natives further underscores this point, as low-level acoustic processing should be common to both groups (i.e.: both groups heard exactly the same experimental materials). It was suggested that anterior to mSTG activation reflects either (1) the actual violation of phrase structure expectancies, or (2) the mismatch between expected and presented word category information. Based on the fact that non-native speakers show less activation here than natives, it is thus postulated that either (1) non-native speakers do not build phrase structure expectancies, or (2) non-native speakers do not have sufficient access to word category information.

6.6 Conclusion

Taken together the results of this experiment indicate that non-native speakers do not rely on the same expectancies concerning up-coming words in spoken sentences (phrase structure expectancies) as do native speakers. In natives such expectancies support a fast and efficient parsing of spoken speech and appear to employ mid to anterior lateral portions of STG. Non-native speakers compensate for this with alternative strategies, which may have their neural correlates in frontal cortices or indeed in a fronto-striatal loop comprising IFG and basal ganglia structures.

Chapter 7

Verbal Working Memory and L2

In the fMRI study presented in Chapter 6, non-native speakers showed greater levels of activation than natives in a network of areas comprising IFG, the head of the caudate nucleus in the basal ganglia, and cortex within the intraparietal sulcus. Increased involvement of structures within the basal ganglia has been reported for non-natives previously (Klein et al., 1994, 1995) and has been interpreted to reflect increased difficulties in articulation. In native speakers the caudate nucleus together with BA44 has been implicated in the premotor articulatory commands underlying covert articulation or rehearsal (Henson, 2001). Therefore, one possible candidate for the alternative strategy used by non-natives to parse spoken sentences could be covert articulation, or silent mental rehearsal. In the following behavioral study, this idea is explored further, namely the notion that non-native speakers of a language rely more heavily on working memory (specifically the phonological loop) in order to processes language successfully than do native speakers.

7.1 Introduction

Working memory (WM), as proposed by Baddeley and colleagues, describes a multi-component short term memory system, supporting the cognitive manipulation of retrieved and incoming new information (e.g.: Baddeley & Hitch, 1974; Baddeley, 1997). The model consists of at least three components: One controlling attentional system, otherwise referred to as the central executive, and at least two subsidiary slave systems, which are monitored by the central executive. The two best described slave systems are (1) the articulatory or phonological loop, which supports the manipulation of speech signals and (2) the visuo-spatial sketch pad, which underlies the construction and manipulation of visual images.

Evidence from both patients with neurological deficits as well as neuroimaging studies with healthy participants have produced a large body of evidence supporting a functional anatomical distinction between the WM components proposed by Baddeley and colleagues (Henson, 2001). It is generally thought that processes underlying verbal WM (i.e.: the phonological loop) are contained within a left lateralized fronto-parietal cortical network (Smith & Jonides, 1997; Henson, 2001; Xue et al., 2004), while those underlying visuo-spatial processing (i.e.: the visuo-spatial sketch pad) are located in the right hemisphere (Jonides et al., 1996; Henson, 2001). Furthermore a distinction has been made between processes of storage and rehearsal in WM. Posterior parietal regions are thought to support the short term storage of information, while portions of frontal cortex (BA44 and premotor cortex) are thought to play a role in the rehearsal of stored items (Henson, 2001). The conceptual distinction between storage and rehearsal in WM can be made clearer by looking more closely at the first of Baddeley's slave systems, the phonological loop.

The phonological loop underlies the cognitive manipulation of speech sounds, for example in segmentation or rhyming. It comprises two components: The phonological store, which is capable of maintaining speech-based information for a brief length of time (approximately two seconds), and an articulatory control process, which underlies covert speech (Baddeley, 1997). These two components work together in order to prepare and maintain information for manipulation by the central executive. The phonological store is a passive storage area, which is erased over time. Through active covert articulation via the articulatory loop, information can be reinfused into the phonological store, prolonging its storage life.

A number of different behavioral effects have been well-documented as evidence for the existence of the phonological loop (i.e.: phonological similarity effect, unattended speech effect, word-length effect, effect of articulatory suppression) (e.g.: Andrade, 2001; Baddeley, 1997). These effects document various speech processing deficits or difficulties as a result of experimentally reduced WM capacity. In the following experiment we made use of the articulatory suppression effect, which is explained here in greater detail.

Articulatory suppression (AS) is a process by which the articulatory loop component of the phonological loop is blocked, thereby disrupting the workings of the phonological loop as a whole. Blockage of the articulatory loop is achieved by having participants covertly articulate speech stimuli irrelevant to the task at hand. This has been shown to have a dramatic effect on performance of tasks relying on WM, including the processing of acoustic speech stimuli, as well as some aspects of written language processing (e.g.: Baddeley, 1997).

That working memory is an integral part of language comprehension is relatively undisputed, however the precise nature of the system remains a matter of debate. Several prominent theories have addressed the specific role of WM in sentence comprehension, and particularly in the parsing of syntactic structure in sentence comprehension (Just & Carpenter, 1992; Caplan & Waters, 1999; Gibson, 1998). The Capacity Theory of Comprehension (CTC: Just & Carpenter, 1992) argues for a working memory system common to multiple cognitive systems, which is utilized to aid in the parsing of sentence structure. Specifically, this single-resource model postulates that participants with a high working memory capacity will be facilitated both in combining incoming information from multiple linguistic domains (i.e.: syntax and semantics) and in deciding between locally ambiguous syntactic structures in sentences. This is due to the fact that multiple interpretations are more easily maintained in working memory until a final decision can be made. In contrast to CTC, the Separate-Sentence-Interpretation-Resource Model (SSIR: Caplan & Waters, 1999) proposes a WM system *specific* to syntactic processing. Syntactic WM is thus proposed to be a highly specialized unit within a greater WM system, the functionality of which is not generally applicable to other domains (Caplan & Waters, 1999). Within syntactic WM a further delineation is made between on-line 'interpretive' processing, which supports the processing of complex syntactic structure, and later 'postinterpretive' processing, which can further manipulate meaning extracted from a comprehended sentence. Caplan & Waters argue that CTC taps into postinterpretive processes only, which may indeed show more overlap with other cognitive domains. The use of WM in interpretive processing, on the other hand, supports on-line syntactic processing and is not shared by other domains.

CTC and SSIR propose various ways in which language processing as a cognitive system might incorporate WM. A more specific suggestion as to what role WM might play in parsing sentence structure is presented in the Syntactic Prediction Locality Theory (SPLT) (Gibson, 1998). SPLT argues that once a word has been parsimoniously integrated into a possible sentence structure, it no longer taps into WM resources. Sentences with long local dependencies (i.e.: filler-gap distances) will thus rely more heavily on WM than sentences with dependencies spanning a smaller distance. Such an account finds support in recent electrophysiological studies (Fiebach et al., 2001, 2002b) .

With regards to second language processing, it has been postulated that verbal WM plays an important role in second language learning (Baddeley et al., 1998), however the focus of such research has generally been on the acquisition of new vocabulary. Specifically, it has been suggested that the phonological loop supports the temporary storage of unfamiliar phonological forms, while more permanent memory representations are being constructed

(Baddeley et al., 1998). Working memory skills have also been shown to correlate to some degree with language aptitude (Miyake & Friedman, 1998), although the specific role of WM in second language processing remains a topic unclear. Importantly, vWM is thought to be one system underlying processing in both L1 and L2 (Xue et al., 2004).

In the following experiment a single resource view of vWM in second language sentence processing was investigated. Participants were asked to make grammaticality judgments on sentences, which they listened to while simultaneously repeating the word 'Pfau' (Engl. *peacock*). The results taken from this experiment were subsequently compared with behavioral results taken from participants conducting the same task in the scanner environment (Chapter 4, Experiment 1).

7.2 Experiment 4A

It is hypothesized that non-native speakers of a language rely more heavily than native speakers on covert rehearsal of incoming speech stimuli in order to process spoken language. Specifically vWM may be used by non-natives to compensate for an inability to quickly detect phrase structure violations on the basis of word category expectancies (see also Hahne, 2001; Kubota et al., 2003). If this is the case, non-native speakers should experience a dramatic decrease in proficiency when asked to make grammaticality judgments on sentences while simultaneously producing an unrelated speech sound in contrast to making the same judgment without simultaneously producing speech sounds. Native speakers, on the other hand, should show no difference in performance, regardless of the additional speech production task.

7.2.1 Participants

Scanner Session
The behavioral results from fifteen native Russian participants and eighteen native German participants were taken from the fMRI experiment described in Chapter 4 (Experiment 1).
Articulatory Suppression Session
Fourteen native Russian speakers (age: 25.4 ± 3.1, 6 males) and eight German native speakers (age: x years, x males), who had not participated in Experiment 1 (Chapter 4), participated in this experiment. Russian natives were proficient in German, and had been living in Germany for an average of 6.7 ± 2.6 years.

7.2.2 Methods and Materials

7.2.2.1 Material

The sentence materials used in this behavioral experiment were identical to the fMRI experiment described previously (see Chapter 4 for description of materials, Table 4.1 for examples). The experimental design differed only in the number of trials used: A reduced number of 96 trials was used as opposed to the 192 trials in the fMRI experiment. Lists consisting of 24 sentences from each experimental condition plus 24 filler sentences were presented to participants. Sentence stimuli were pseudorandomized so that no condition was repeated consecutively more than three times, and correct and incorrect answers were repeated consecutively no more than four times. Each list was broken down into 3 blocks of 32 sentences. The number of trials belonging to each condition was balanced across blocks. Each list of 96 sentences could be presented forwards and backwards, yielding 2 different lists with which to present participants.

7.2.2.2 Procedure

Participants were given headphones and seated in front of a monitor in a quiet room. Prior to beginning the experiment, participants were instructed as to the task. Participants were told that they would hear a number of sentences, some of which were correct, some semantically incorrect and some syntactically incorrect. While listening to the sentences, participants were instructed to repeat aloud the word ”Pfau”(engl. *peacock*). Participants were instructed to listen carefully to the sentences, to determine whether or not the sentences were acceptable and then to press one of two buttons to indicate their answer. Participants were not asked to differentiate between syntactic and semantic errors.

Each trial was introduced by a fixation cross, which appeared on the monitor for 400 ms prior to sentence initiation. Upon disappearance of the fixation cross, a sentence was presented over the headphones. Immediately following the auditory information, question marks appeared on the screen, indicating that participants should make their judgment. Half the participants receiving each list answered with their right hand for correct sentences and half answered with their left. Reaction times and responses were recorded. Reaction times, however, do not reflect on-line processing and are not discussed further, as participants were told to wait until prompted to give their responses.

Table 7.1: Error Rates and Reaction Times (± Standard Error) for the native (L1) and non-native (L2) speakers in the three experimental conditions (COR, SEM, SYN). Participants were measured in two sessions: One in the noisy scanner environment (fMRI) and one in which participants engaged in articulatory suppression (ASUP).

		Percent Correct			Reaction Times (ms)		
		COR	**SYN**	**SEM**	**COR**	**SYN**	**SEM**
fMRI	**L1**	97 ± 0.7	95 ± 0.8	94 ± 1.7	367 ± 19	369 ± 19	401 ± 19
	L2	85 ± 2.2	76 ± 4.7	86 ± 2.1	478 ± 34	494 ± 47	538 ± 42
ASUP	**L1**	94 ± 1.8	91 ± 3.1	89 ± 2.4	380 ± 52	353 ± 55	350 ± 51
	L2	85 ± 1.7	47 ± 6.8	87 ± 2.6	317 ± 20	372 ± 36	309 ± 21

7.2.3 Results

Repeated measure ANOVAs were calculated using error rates with the between-subject factors Group (L1,L2) and Session (fMRI,WM) and the within-subject factor Condition (COR,SEM,SYN). An overview of the performance rates can be seen in Table 7.1 and Figure 7.1. Reaction times are also provided in Table 7.1, however they will not be discussed further, as they are not an indication of on-line sentence processing. A Greenhouse-Geiser correction of the significance level was made for all repeated measures comparisons showing unequal variances. Corrected p-values are reported.

Both Groups of participants were affected to some degree by the WM manipulation, as indexed by a significant main effect of Session [F(1,51) = 8.43; $p < 0.01$]. Furthermore the L2 speakers were significantly worse than L1 speakers across conditions, as seen in the significant main effect of Group [F(1,51) = 49.83; $p < 0.0001$]. A significant main effect of Condition was also present [F(2,102) = 27; $p < 0.0001$]. Critically, participants in each of the Groups showed differences in performance on specific Conditions as a function of the Session, as seen in the highly significant three-way interaction between Group x Session x Condition [F(2,102)= 9.01; $p < 0.005$]. The significant three-way interaction allowed us to conduct further analysis within each Group separately.

Within the L1 Group, a small but marginally significantly difference between error rates in the two Sessions was seen, performance being slightly worse in the articulatory suppression Session [F(1,24)=3.18; p = 0.08]. Furthermore, there was a difference between performance rates relating to specific Conditions, as seen in a main effect of Condition [F(2,48)=5.19 $p < 0.001$]. This effect was the result of better performance rates for Condition COR than Condition SEM across Sessions [F(1,24)=7.82; $p < 0.016$, Bonferroni corrected alpha value)]. There was no difference in L1 participants' response to the different

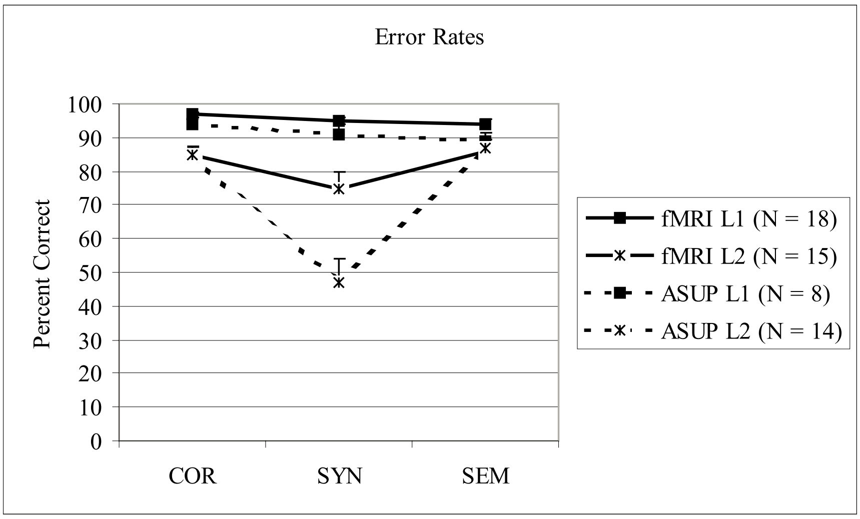

Figure 7.1: Performance rates of native (L1) and non-native (L2) participants in judging sentence acceptability while lying in the scanner (fMRI) and during the articulatory suppression task (ASUP). Participants heard correct sentences (COR), syntactically incorrect sentences (SYN) and semantically incorrect sentences (SEM).

Conditions as a function of Session (no significant interaction between Session x Condition F(2,48) < 1; p = 0.67).

Within the L2 Group, participants were worse at the experimental task during the articulatory suppression manipulation as seen in a main effect of Session [F(1,27) = 6.51; $p < 0.05$]. Furthermore there was a difference between performance rates in the different sentence Conditions, as seen in a main effect of Condition [F(2,54)=35.24; $p < 0.0001$]. This reflected a significant drop in performance rates in both Sessions for Condition SYN compared to either COR [F(1,27) = 32.86; $p < .0001$, Bonferroni corrected alpha value] or SEM [F(1,27) = 47.74; $p < .0001$, Bonferroni corrected alpha value]. Crucially, the difference in performance between the SYN Condition and the other two Conditions was far greater in the ASUP Session than in the fMRI Session, as seen in the significant interaction between Session x Condition [F(2,54)=12.16; $p < 0.0001$].

The significant interaction between Session x Condition in the L2 Group was resolved by looking at differences in responses to each Condition across Sessions. There was no difference between error rates in response to correct sentences in the two Sessions [F(1,27) < 1, p = 0.9], or in response to semantically anomalous sentences [F(1,27) < 1, p = 0.8].

L2 speakers made significantly more errors in detecting syntactically anomalous sentences in the ASUP Session than in the fMRI Session [F(1,27) = 12.16, $p < 0.005$].

7.2.4 Discussion

The current behavioral experiment was designed to explore the role of the verbal working memory, described in Baddeley's WM model, in spoken language processing. Specifically it was of interest whether or not verbal working memory could be shown to play a different role in the processing of a native vs. a non-native language.

The results described here show that articulatory suppression affects sentence processing in L1 and L2 speakers differently. Both groups were somewhat affected by the task, as seen by the main effect of session in the performance rate data. However, while L1 speakers experienced a small, only marginally significant decline in proficiency rates, in all experimental conditions, L2 speakers were specifically impaired in detecting syntactic anomalies (see also Figure 7.1). Therefore it is proposed that the articulatory suppression task selectively affected L2 speakers in the processing of phrase structure violations. Consequently it is proposed that L2 speakers draw on vWM resources to parse syntactic structure in spoken language comprehension to greater extent than natives.

The sentences used in this study were used previously in a series of ERP studies with both native and non-native speakers. In response to syntactic violations, native speakers showed two distinct ERP components: One very early negativity over left frontal electrode sites (ELAN: peak ca. 150 ms post stimulus onset), and a later, more broadly distributed positive signature, which was strongest over parietal electrodes (P600: peak ca. 600 ms post stimulus onset) (Friederici, 2002). The ELAN has been discussed as reflecting a very fast, efficient and automatic step in native language processing (Hahne & Friederici, 1999). Specifically it is thought that the ELAN reflects the automatic detection of phrase structure violations (Friederici et al., 1996; Hahne & Friederici, 1999; Friederici, 2002). In the case of the sentences used here the presentation of a participle in a sentence position requiring a noun phrase constitutes a direct violation of the phrase structure expectancy, which elicits a reliable ELAN signature in native German speakers. The ELAN is followed by a positive waveform, dubbed the P600. The P600 has been observed in countless studies, and is thought to reflect controlled, non-automatic processes of syntactic reanalysis and repair or syntactic integration (Osterhout et al., 1994; Kaan et al., 2000; Friederici, 2002).

Non-native speakers show a slightly different pattern of responses to syntactically violated sentences. Specifically, the early automatic ELAN component is not elicited in non-native speakers, while the later, more controlled P600 is (Hahne, 2001; Hahne & Friederici, 2001). This has been interpreted as evidence that non-native speakers are not capable of detecting word category, or phrase structure violations in the same automatic manner as seen in native speakers. Non-natives do, however, compensate in some manner, as their performance rates show that they do indeed detect the syntactic violation (Hahne, 2001; Hahne & Friederici, 2001). Similar results have been obtained using magnetoencephalography to measure native and non-native speakers of English (Kubota et al., 2003, 2004).

The results of the current study indicate that the alternative strategy implemented by non-native speakers to parse syntactic structure, could indeed be based on vWM. As described in the introduction to this chapter, vWM is a short term memory system underlying the cognitive manipulation of speech sounds. Incoming items can be maintained in this memory system for up to two seconds, after which they must be 'updated' through covert articulation via the articulatory loop. By rendering the articulatory loop dysfunctional by means of an articulatory suppression (AS) task, cognitive tasks requiring the support of vWM can be identified: Specifically, participants demonstrate poor performance in those tasks dependent upon vWM, if vWM is made inaccessible.

In the current study the effect of articulatory suppression on judging the correctness of spoken sentences was different in native and non-native speakers. Native speakers showed only a very marginally significant effect ($p = 0.08$) of the AS task. The effect elicited in L1 speakers' performance was consistent across sentence conditions. In other words the judgment of correct, syntactically incorrect and semantically incorrect sentences was affected equally by articulatory suppression. This was not the case for L2 speakers. The performance of L2 participants in response to syntactically anomalous sentences was selectively affected by articulatory suppression. Articulatory suppression did not affect processing of correct or semantically anomalous sentences. This suggests that while native language processing of simple sentences was largely independent of vWM (demonstrated by the lack of a significant effect between sessions), the non-native syntactic processing system, at least the portion responsible for the parsing of phrase structure, is uniquely dependent on access to the vWM system. This dependency might take one of the following forms: (1) incoming speech items are maintained in the vWM circuitry (via covert articulation) until a point in the sentence is reached at which the non-native listener can propositionalize statements, and only then determine whether the syntactic structure of incoming words is in all respects parsimonious; (2) acoustic word forms are maintained in verbal working memory whilst a delayed access to morhphosyntactic information and ultimate lexical selection is carried out. This will be addressed further in Chapters 8 and 9.

A possible alternative account of the results, in particular in relation to the marginal decline in performance in the L1 group, comes from the motor theory of speech perception (MT) (Liberman et al., 1967; Liberman & Mattingly, 1985). MT proposes that the perception of speech on the phonological level is dependent upon the same processes underlying speech production. Specifically, incoming speech stimuli are suggested to be processed by the listener via neuromotor commands to the articulators (mouth, vocal tract, etc.). These neuromotor commands do not instigate an actual movement of the articulators, rather they can be understood as premotor planning of articulatory movements (or gestures). MT, in its original form, addresses the phenomenon of phoneme categorization, in which speech sounds with different physical properties (due, for example to co-articulation with various other phonemes) are nevertheless perceived as the same phoneme (see further Liberman & Mattingly, 1985; Diehl et al., 2004; Jusczyk & Luce, 2002).

The articulatory suppression task clearly relies on neuromotor commands to the articulators, as it calls for the overt production of an irrelevant word. MT claims that overt articulation of the unrelated word monopolizes neuromotor planning of gestures, rendering this system useless in aiding in phoneme discrimination. Speech perception on the phonological level is thus made more difficult, and performance should decline in all language comprehension tasks. The difference between sessions in the native groups reached only marginal significance in all sentence conditions. The possibility is left open that more subjects might enhance the reliability of an effect across all conditions. This would be evidence for some effect of speech perception along MT lines. However, this account cannot account for the non-native data. Articulatory suppression had no effect on the accuracy of L2 speakers' responses to correct or semantically anomalous sentences. It selectively affected the processing of syntactic anomalies alone in this experiment.

To summarize: Articulatory suppression affected native language comprehension differently than non-native language comprehension. L1 speakers showed no reliable change in performance rates in a language comprehension task conducted in conjunction with an articulatory suppression task. L2 speakers, on the other hand, showed a specific decrease in performance levels in judging syntactic errors as an effect of articulatory suppression. The vWM account of this selective effect maintains that L2-speakers rely specifically on vWM in order to parse syntactic structure. In the case of correct and semantically anomalous sentences, a correct decision can be made by the participant *without* paying any attention to syntactic information (i.e.: by relying on lexical-conceptual information alone). This is not true for syntactic anomalies. The MT account of the non-native results maintains that premotor commands aid in the parsing of syntactic structure. There is no plausible reason to assume this. Since MT describes perception of language on the phonological level, anything disrupting MT perception should affect all higher levels of processing. The selective interference of articulation with syntactic parsing is not easily dealt with in the MT account.

There is one further point which should be addressed here: The articulatory suppression task introduced a superfluous speech element into the experimental setting. This is important for two reasons: (1) listening to speech is not the same as listening to other acoustic stimuli (such as that elicited by the scanner) (i.e.: Liberman & Whalen, 2000; Kopp et al., 2004), and (2) the nature of the phrase structure violation used in this experiment. The syntactic error was created by initiating a prepositional phrase, which requires a complementary noun (see also the description of materials in Chapter 4). Said differently, the syntactic error was created by *omitting* a requisite noun. In the articulatory suppression task, participants were required to produce a word belonging to exactly this missing word category. Therefore, it is feasible that the selective drop in performance rates related to syntactic anomalies has to do with the fact the noun produced during articulatory suppression in some way interacts with detection of the word category violation. This issue is addressed in the Experiment 4B.

7.3 Experiment 4B: External Language Manipulation

The results from Experiment 4A point to a direct effect of articulatory suppression in parsing syntactic structure of spoken sentence in a non-native language. Articulatory suppression is intended to directly affect the function of vWM, however it is possible that the task simply introduced linguistic information into the system, which interacted specifically with the detection of the word category violation in this experiment (see also Kopp et al., 2004). Participants clearly perceive the word they are asked to produce, and it is possible that the perception of a noun interacts with the processing of syntactic structure– particularly in the case of word category violations constructed on the basis of omitting a noun.

We tested this hypothesis in a second experiment, in which participants listened to exactly the same sentence materials in the same experimental conditions as described previously, however instead of having participants say ”Pfau”while listening to sentences, the experimenter sat next to the participant and said this word aloud. In this way linguistic interference was matched, but in one case vWM was suppressed (via articulatory suppression), and in the second there was no vWM manipulation (this session is referred to from now on as LANG).

If the effects of Experiment 4A are due to production or perception of the extra noun introduced by the AS task, then a similar interaction between results from the scanner session and results from the LANG session is expected. Participants should be selectively worse at detecting syntactic errors. If the effect recorded in Experiment 4A is not due to the introduction of a noun into the experimental environment, we expect to see no interaction between the sessions. Specifically, there should be no significant difference between sessions in the detection of syntactic anomalies.

7.3.1 Participants

Scanner Session
The behavioral results from fifteen native Russian participants and seventeen native German participants were taken from the fMRI experiment described in Chapter 4 (Experiment 1). One of the German native participants was left out of the analysis because he completed only 2 of 3 blocks in the scanner session.
Language Interference Session
Twenty native Russian speakers participated in this experiment initially. Six participants were subsequently excluded for making too many errors, leaving us with a final group of fourteen native Russian speakers (age: 22.7, 6 males). Russian natives were proficient in German, and had been living in Germany for an average of 6 years and learning German for 7 years on average.

7.3.2 Methods and Materials

7.3.2.1 Material

The same sentence material as was used in Experiment 4A was used in this experiment.

7.3.2.2 Methods

The experimental set-up and procedure was identical to that of Experiment 4A with one difference: Participants did not engage in articulatory suppression. Instead of producing the irrelevant word 'Pfau', participants heard an outside observer (the experimenter) produce the word 'Pfau'.

7.3.3 Results

A repeated measures ANOVA was calculated with the between-subjects factor Session (fMRI, LANG) and the within-subjects factor Condition (COR, SYN, SEM).

No significant main effect of Session was observed [$F(1,27) < 1$, $p = 0.8$]. Participants in both groups were worst a judging syntactic anomalies, as reflected in a significant main

Table 7.2: Performance rates of non-native (L2) participants in judging sentence acceptability while lying in the scanner (fMRI) and during the language interference session (LANG). Participants heard correct sentences (COR), syntactically incorrect sentences (SYN) and semantically incorrect sentences (SEM).

		Percent Correct			**Reaction Times (ms)**		
		COR	**SYN**	**SEM**	**COR**	**SYN**	**SEM**
L2	**fMRI**	85 ± 2.2	76 ± 4.7	86 ± 2.1	478 ± 34	494 ± 47	538 ± 42
	LANG	87 ± 2.1	64 ± 9	93 ± 1.5	458 ± 39	501 ± 51	489 ± 37

effect of Condition [F(2,54) = 16.27, $p < 0.0005$]. Furthermore participants responded to the different Conditions differently depending on which Session they took part in, as reflected in a marginally significant interaction between Session x Condition [F(2,54) = 3.21, $p < 0.08$].

The interaction is only marginally significant, however because it is crucial to the interpretation we resolved the interaction by looking at differences between the two Sessions in each experimental condition. There was no difference in performance accuracy between the two Sessions in response to either correct sentences [$F(1,27)<1$, p = 0.5] or in response to syntactically incorrect sentences [F(1,27) = 1.29, p = 0.2]. L2 speakers were, however significantly better at judging semantically anomalous sentences outside of the scanner environment [F(1,27)=6.03, $p < 0.05$].

7.3.4 Discussion

The results of this experiment indicate that the introduction of a linguistic distractor (the word 'Pfau') does not selectively degrade non-native speakers' performance in detecting word category violations. The marginally significant interaction observed in the results recorded from the two sessions can be shown to be the effect of increased performance in the detection of semantic violations outside of the mechanically noisy scanner environment.

7.3.5 General Discussion and Conclusions

The aim of this behavioral study was to investigate the dependency of native vs. non-native speakers on vWM in spoken language comprehension. The functional resources provided by vWM were blocked through an articulatory suppression task. The results showed a slight decline in performance for native speakers in language comprehension per se as a result of AS. No distinction could be drawn between syntactic or semantic processing. Non-native

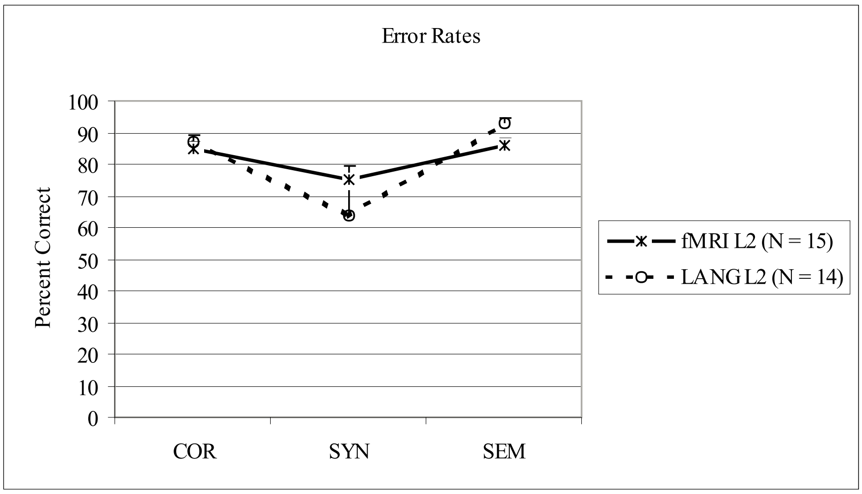

Figure 7.2: Performance rates of non-native (L2) speakers while judging sentences in the scanner (fMRI) and during the language interference session (LANG). Participants were instructed to make an acceptability judgment on correct (COR), syntactically anomalous (SYN) and semantically anomalous (SEM) sentences.

speakers, on the other hand, were selectively affected in their parsing of syntactic structure as a result of AS. Processing of semantic information was unaffected by AS.

If we assume that AS selectively affected the function of vWM, the results are quite clear: VWM plays a small but significant role in the comprehension of spoken sentences for native speakers, but is a necessity for the parsing of syntactic structure in non-native speakers of a language. However AS, although shown to very reliably affect participants on tasks relying on vWM (Baddeley, 1997), may have interfered with language processing on other dimensions as well. Specifically, the reliance of AS on the participant's simultaneous production and comprehension of speech invites a discussion of the results against a background of Alvin Liberman's MT (Liberman & Mattingly, 1985; Liberman & Whalen, 2000). As reviewed in the discussion of Experiment 4A, MT postulates that the human language production and comprehension systems are shared at the level of premotor articulatory gestures and that the perception of speech sounds is unique in the human auditory system– in other words, that speech stimuli are processed in a distinct manner to other acoustic stimuli (Liberman & Mattingly, 1985). In its original form, MT addressed the question of how and why phoneme categorization occurs in language perception. Several major challenges to MT have been made, most prominently the findings that (1) phoneme categorization is not necessarily a uniquely human ability (i.e.: Ramus et al., 2004), (2) some effects regarding coarticulation (duplex perception) not unique to speech (Diehl et al., 2004). Nevertheless, the idea that language production and comprehension must share something is intriguing, and recent thoughts on the role of so-called mirror neurons in shaping the language system have revived interest in MT (Rizzolatti & Arbib, 1998; Liberman & Whalen, 2000).

MT in its purest form would assume that the production of a word in the AS task dominates neuromotor commands to the articulators. The same neuromotor commands aid, however, in the phonological perception of incoming speech stimuli. Therefore, during language production, language comprehension will be impeded at the level of phonological perception. The results of Experiment 4A show such an effect for non-native speakers. It cannot be ruled out that the production of speech in this experiment therefore led to a general decline in the capacity of native speakers to perceive incoming speech stimuli. An overall decline in speech perception is not, however, observed in the non-native group. Non-native speakers were selectively impaired in their parsing of syntactic structure, in particular in the detection of phrase structure violations.

MT as a mapping of phoneme perception onto production by way of articulatory gestures does not predict a selective interference of speech production on syntactic processing, and an interference with speech perception *per se* is not induced in non-native speakers by AS. Therefore, at least in non-native speakers, AS does not appear to have a degrading effect on speech perception as predicted by MT. One interesting point to keep in mind here, is that MT talks specifically about speech perception at the phonological level. It is precisely this level of language processing which is most difficult to acquire in a second language. Phoneme categorization has been shown to be experience-related, meaning that native speakers do not necessarily recognize phoneme boundaries from other languages, if these boundaries do not occur in their native language (Winkler et al., 1999). Secondly, non-native speakers are greatly challenged by the production of phonemes in their non-native language, as seen in the persistence of foreign accents. Is it possible that non-native speakers therefore cannot perceive language along the same lines as natives, in precisely the manner described by MT? The results of the current study could be taken to suggest that perception of speech was marginally influenced per se by production in natives (evidence for perception along MT lines), but that perception of speech was not influenced in non-natives (no perception along MT lines).

So far the evidence in the non-native group points towards a specific role of vWM in parsing syntactic structure. There is, however another confounding issue related to the AS task, namely the fact that participants were instructed to produce a noun– precisely that word category which is missing in the sentences containing a phrase structure violation. Could it be that the introduction of this syntactically relevant speech element into the experimental setting interfered specifically with syntactic processing? The results of Experiment 4B show that this is not the case. Having participants judge sentences while simultaneously listening to someone else produce the same noun had no effect on performance in judging syntactic errors. Non-native speakers in this session were better at identifying semantic errors in sentences than those participants who took part in the fMRI experiment. This is easily explained by the fact that there is clearly far more acoustic interference from the non-speech noise generated by the scanner. Non-native speakers have been shown in other studies to experience increasing difficulty in comprehending spoken language with increasing background noise (Mayo et al., 1997; Meador et al., 2000; Lin et al., 2004). Therefore the reduction in background noise in the LANG session may have facilitated non-native speakers' perception of spoken sentences.

Chapter 8

Lexical Selection and L2

Non-native speakers in the previous study were observed to experience no interference of limited irrelevant speech stimuli on the comprehension of short grammatically plausible sentences. Native speakers, however, were slightly impaired in their comprehension of simple sentences. It was suggested that (1) non-native speakers may be unable to perceive speech in the manner outlined by MT, which specifically attempts to explain the phenomenon of phoneme categorization (Liberman & Mattingly, 1985), and (2) that non-native speakers are very dependent on semantic information in making sentence acceptability judgments.

The following study picked up on these two issues together. First, it has been shown previously that speakers have difficulties in perceiving and categorizing phonemes in a non-native language (Sebastian-Galles & Soto-Faraco, 1999; Dehaene-Lambertz et al., 2000; Sebastian-Galles & Bosch, 2002). If non-native speakers are unsure of precisely which phoneme has been produced in a word, then lexical selection cannot proceed as efficiently as in native speakers. Secondly, non-native speakers must compensate for their shortcomings in phoneme perception with alternate strategies. One candidate for such a strategy is a greater reliance on sentence context. These issues were addressed by investigating whether non-native speakers were differentially influenced by the existence of phonological neighbors for semantically implausible words in spoken sentences. The goal of the study was to investigate whether top-down contextual information influences lexical selection in acoustically presented sentences to a greater degree in non-native than native speakers.

8.1 Introduction

There is an ongoing debate in the field of auditory speech perception concerning the extent to which higher order information (such as sentence context) can influence incoming lower level information (such as phoneme perception or lexical selection). This debate is characterized by two extreme positions, one arguing for modularity and one arguing for interactivity in language processing. Proponents of *modularity* argue for a cognitive processing architecture, in which autonomous perceptual systems process subsets of information, the output of which is integrated at a higher processing level (e.g.: Fodor, 1983). In the language processing system, information is always passed forwards along an information continuum, and feedback from later processing steps (or modules) cannot influence earlier processing steps (Frazier & Fodor, 1978; Frazier, 1987). Modular models, such as the Race Model (Cutler & Norris, 1979) or the Merge Model (Norris et al., 2000), have additionally implemented multiple forward routes and decision-making levels, in which information from multiple lower-level modules is merged before being subjected to further processing in order to explain some of the data not addressed by earlier models. *Interactive models,* on the other hand, argue for a continuous sharing of information between different computational levels, thus allowing for higher order information to influence lower level processing. Lexicality effects on phoneme detection, for example, are explained in interactive models by the top-down influence of lexical access on lower-level phoneme perception (i.e.: TRACE Model: McClelland & Elman, 1986). As is generally the case, good evidence exists for a language processing architecture lying somewhere in between the two extremes. Several researchers argue, for example, for a system in which there is interactivity between lexical and phonological processing levels, but modularity at the sentence level (Connine, 1995; Samuel, 1995).

Importantly, both modular and interactive models can account for context effects at the behavioral level. Modular models see the role of context in a post decision process, in which several possible outputs from a given level are kept active until a merging of these possibilities with context information in a late, decision-making node allows for the selection of one alternative. In this manner the input into a lower level is never directly altered, rather a decision-making node is required to use additionally gathered information to select from a set of possible alternatives (Swinney, 1979; Zwitserlood, 1989). Interactive models, on the other hand, hypothesize that a prior decision making process takes place, in which contextual information is used to literally alter lower-level processes. For example, a phoneme restoration effect has been described, in which sentential context can actually bias the speech processing system into thinking it is perceiving something that it is not (Warren, 1970).

On the neurophysiological level, different cortical regions have been observed to support low level processes, such as acoustic perception of speech signals, and higher level processes, such as strategic syntactic or semantic processing (for a review see Binder & Price, 2001). Low level processes tend to be localized in primary association cortices, surrounding primary sensory cortices. For example, it has been shown that areas directly lateral to the primary auditory cortex in the STG are sensitive to complex auditory signals including, but not restricted to, speech (e.g.: Binder et al., 2000), while more ventral portions of left STG, extending into STS and MTG appear to be increasingly selective about what specific aspects of speech processing they support (Binder et al., 2000; Scott & Johnsrude, 2003). A specific involvement of the planum temporale (PT), a region in the dorsolateral supratemporal plane, just posterior to primary auditory cortex, has been suggested in L1 phoneme perception (Hickok & Poeppel, 2000; Buchsbaum et al., 2001; Jäncke et al., 2002). Higher level linguistic functions have been shown to activate frontal cortices, in particular the left IFG is seen to be increasingly involved in the strategic processing of linguistic information on a number of different levels (phonology, semantics and syntax) (Bookheimer, 2002; Friederici, 2002).

Several neuroimaging studies looking at second language processing have reported increased levels of activation in IFG for participants listening to language stimuli in their non-native language (Yetkin et al., 1996; Marian et al., 2003; Perani et al., 2003; Wartenburger et al., 2003; Rüschemeyer et al., in press). There are several plausible explanations for an increased involvement of IFG in processing a non-native language, including increased task difficulty, increased effort in categorizing phonemes, and increased difficulty in lexical selection. The behavioral study described here picks up on two of these, namely increased difficulty in lexical selection *due to* difficulty in phoneme categorization.

This difficulty in lexical selection does not refer to unfamiliarity with words in L2. Rather, it entertains the notion that lexical selection in non-natives suffers due to a lack of accuracy and efficiency on the part of non-native listeners in categorizing phonemes. It has been shown previously that the ability of non-native speakers to correctly categorize phonemes in their non-native language is influenced by age of acquisition and exposure to the second language (Flege et al., 1999), and furthermore that the given ability of a non-native speaker to discriminate between phonemes in the non-native language accounts for a significant amount of observed variance in spoken word recognition (Meador et al., 2000). Non-native speakers therefore have a deficit in the information available to them at the phonological level, and this influences word recognition.

It has been suggested that deficits on any of the processing levels leading up to lexical selection can be compensated for by a greater reliance on information from an intact functional processing level (Stanovich, 1980). Studies investigating word recognition in both written (Stanovich et al., 1985; Holcomb et al., 1992) and spoken (Holcomb et al., 1992) language processing have, for example made the argument that young children, less adept at reading and less familiar with language per se, depend on sentence context to a greater extent in driving lexical selection than do adults.

We incorporate observations concerning the level of processing difficulty in non-native speakers (phonological categorization) with the idea that sentence context may eliminate shortcomings on the phonological level. Specifically we suggest that the deficiency on the *phonological* level will lead non-native speakers to initially activate a larger number of *phonologically* similar lexical alternatives. In other words, a non-native listener is not as proficient at mapping incoming speech signals onto existing phonemic representations. Because of this a greater set of phonologically similar alternatives must be kept available until (sentence) context can guide the selection processes in making a final decision. It has been shown that the existence of phonological neighbors influences word processing in native speakers as well (Luce et al., 1995), however it is hypothesized here that non-native speakers will be prone to significantly more interference in lexical selection brought on by phonological neighbors. If it can be shown that a greater set of lexical alternatives from which to choose is available to non-native speakers than to natives, this could lend credibility to the lexical selection hypothesis discussed previously.

8.2 Hypothesis

It is hypothesized that non-native speakers rely less on bottom-up acoustic cues and more on top-down sentence context to drive lexical selection in auditory sentence processing. To test this, sentences were created with semantically anomalous nouns, some of which had a close phonological neighbor (a minimal pair) which was semantically plausible in the given sentence context, and some of which had no such phonological neighbor. The hypothesis is that non-native listeners will more readily judge as correct those semantically incongruous words which have semantically acceptable phonological neighbors than will native speakers.

8.3 Methods

8.3.1 Material

A total of 160 sentences were constructed for this experiment (for examples see Table 8.1). The 160 sentences consisted of 80 correct and 80 semantically incorrect sentences. All sentences were in the passive voice in German, and were kept as similar as possible in form to the sentences used in the fMRI experiments described previously. Long and short versions of all experimental conditions were constructed, as shown in the examples. In the long version of the semantically violated sentences, the anomaly could occur on either the first or the second noun phrase (NP).

The experimental manipulation was contained within the semantically incorrect sentences. These were broken down into (1) 40 sentences containing a ”pure”semantic error (SEM), and (2) 40 sentences in which the semantically anomalous noun had a minimal pair, which would render the sentence plausible (PHON). In other words, anomalous nouns in these sentences had a very close phonological neighbor which would not be anomalous in the sentence context. Minimal pairs refer to words with entirely different meanings, whose acoustic parameters differ in only one phoneme. In the example provided in Table 8.1 the phonological condition is illustrated by the following sentence: Der Tisch wurde geangelt. (Engl.: The table was caught.) The German word *Tisch* (Engl.: table) builds a minimal pair with the word *Fisch* (Engl.: fish), as Tisch and Fisch are differentiated only by the initial phoneme /t/ vs. /f/. While it is semantically implausible to catch a table, normal speakers have no problem with the concept of catching a fish. Thus the PHON condition was constructed in such a manner that sentence context could bias listeners to thinking they had heard a semantically congruous, phonologically related alternative. Participants were told only that some sentences were semantically incongruent– they were naive to the phonological manipulation.

Forty verbs were used to create sentences in each of the experimental conditions, plus an equal number of correct sentences, making a total of 160 sentences. All nouns were matched for length and frequency according to the CELEX database. The 160 sentences were split into two lists of 80 sentences each, with each verb occurring exactly twice in a given list. The occurrence of experimental trials was matched across the lists. Each list thus contained a total of 20 sentences from each experimental condition plus 40 correct sentences. Trials were pseudorandomized in such a manner that no condition was repeated consecutively more than three times, correct and incorrect answers were repeated consecutively no more than four times, and the frequency with which each condition followed another was balanced. Each list was broken down into 2 blocks of 40 sentences. The number of trials from each condition was balanced across blocks. Each list of 80 sentences was presented forwards and backwards, and two different randomizations were achieved, making a total of 4 different possible lists.

Table 8.1: Sentence Materials: Examples of the sentence materials (COR = correct sentences, SEM = semantically violated sentences with no plausible phonological neighbor, PHON = semantically violated sentences with a plausible phonological neighbor) presented in German plus their English translation equivalents. English translations maintain their original word order.

	Short	**Long**
COR	Der Fisch wurde geangelt. *the fish was caught*	Der Fisch wurde im See geangelt. *the fish was in-the lake caught*
SEM	Das Gebäude wurde geangelt. *the building was caught*	Das Gebäude wurde im See geangelt. *the building was in-the lake caught*
PHON	Der Tisch wurde geangelt. *the table was caught*	Der Fisch wurde im Tee geangelt. *the fish was in-the tea caught*

8.3.2 Participants

Thirty-one Russian natives (L2) and twenty-four German natives (L1) (age: 24.5 years, 12 males) participated in this experiment. Five L2 speakers were excluded from the experiment due to high error rates (less than 70 percent correct). This left a total of twenty-six participants (10 males, 16 females) in the L2 group (age: 25.6 ± 3.5 years). L2 participants were highly proficient in German, had been living in Germany for 7 years on average and learning German for an average of six years.

8.3.3 Procedure

Participants were given headphones and seated in front of a monitor in a quiet room. Prior to beginning the experiment, participants were instructed as to the task. Participants were told that they would hear a number of sentence, some of which were semantically incorrect. They should listen carefully to the sentences, determine whether or not the sentence was semantically plausible, and then press one of two buttons to indicate their answer. Participants were not informed of the phonological manipulation in some of the semantically violated sentences. When the participant was ready a short training session, consisting of 8 trials, was run.

Each trial was introduced by a fixation cross, which appeared on the monitor for 400 ms prior to sentence initiation. Upon disappearance of the fixation cross, a sentence was presented over the headphones. Immediately following the auditory information, question

Table 8.2: Performance Rates and Reaction Times (and Standard Error) for the native (L1) and non-native (L2) speakers in the two experimental conditions (SEM, PHON).

	Percent Correct				**Reaction Times (ms)**			
	PHON		**SEM**		**PHON**		**SEM**	
	SHORT	**LONG**	**SHORT**	**LONG**	**SHORT**	**LONG**	**SHORT**	**LONG**
L1	89 ± 1.8	88 ± 2.0	98 ± 0.6	97 ± 1.2	421 ± 17	427 ± 18	369 ± 14	344 ± 13
L2	80 ± 2.4	75 ± 3.3	93 ± 1.8	96 ± 1.3	565 ± 22	540 ± 21	413 ± 15	411 ± 14

marks appeared on the screen, indicating that participants should make their judgment. Half the participants receiving each list answered with their right hand for correct sentences and half answered with their left. Reaction times and responses were recorded.

8.4 Results

Based on the hypothesis and experimental design, repeated measures ANOVAs were calculated with the between subjects factor Group (L1,L2) and within subjects factors Condition (PHON,SEM) and sentence Length (LONG,SHORT). An overview of the results (percent correct and reaction times in milliseconds) can be seen in Table 8.2 and in Figure 8.1. Reaction times are not an indication of on-line sentence processing, as participants were asked to give their answers only after the end of the sentence.

8.4.1 Error Rates

L2 participants made more errors than L1 participants in both experimental conditions, seen in a significant main effect of Group [F(1,49)=17.03; $p = 0.0001$]. Participants in both Groups made significantly more errors in judging sentences in the PHON condition, as seen in a significant main effect of Condition [F(1,49)=90-13; $p < 0.0001$]. No main effect of Length was observed. Crucially, the difference in error rates between the two conditions was greater in the L2 Group than in the L1 Group, exemplified by a significant Group x Condition interaction [F(1,49)=8.02; $p < 0.01$]. Neither two-way interaction involving the factor Length reached significance. There was some indication that Length might influence the processing of sentences in the different Conditions differently in each of the two Groups,

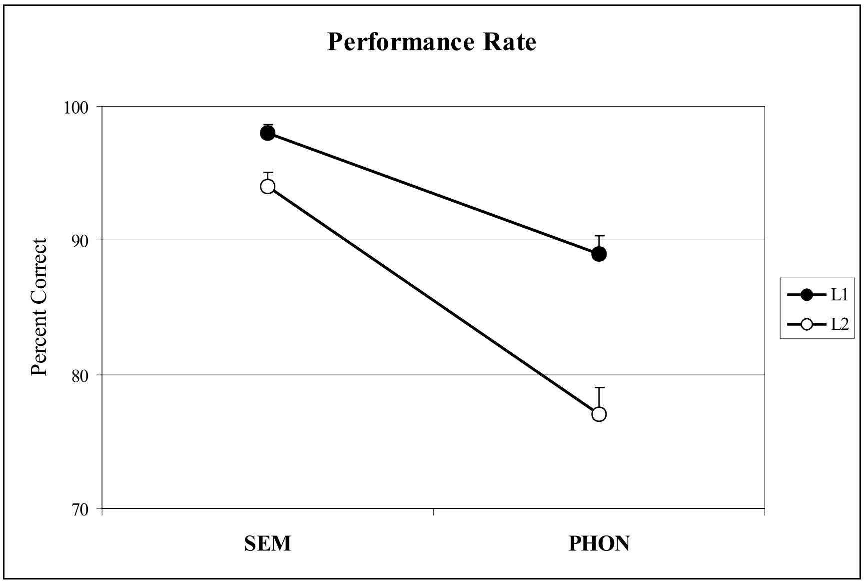

Figure 8.1: Performance rates and standard error for native (L1) and non-native (L2) speakers making judgments on sentences containing either a pure semantic error (SEM), or a semantic error with a semantically plausible phonological neighbor (PHON).

however, as seen in a marginally significant three-way interaction between Group x Condition x Length [F(1,49)=3.25; p = 0.07].

The three-way interaction was resolved by looking for differences in the behavioral data pertaining to Condition and Length within each Group. In the L1 Group this analysis revealed only that participants made more errors in the PHON condition than in the SEM Condition, as seen in a significant main effect of Condition [F(1,24)=49.38; $p < 0.0001$]. No main effect of Length and no significant interaction between Condition x Length was observed. In the L2 Group participants also made more errors in responding to PHON than to SEM, as seen in the main effect of Condition [F(1,25)=50.41; $p < 0.001$]. Length *per se* did not influence error rates significantly (no main effect of Length), however Length seemed to exercise differential influence on behavioral data within the two Conditions as reflected in a significant Condition x Length interaction [F(1,25)=5.37; $p < 0.05$]. The further resolution of this interaction, however produced no significant effects of Length in either sentence Condition.

8.4.2 Reaction Times

L2 participants were slower than L1 participants in responding to sentences in both experimental conditions, seen in a main effect of Group [F(1,49)=6.28; $p < 0.05$]. Both L1 and L2 speakers were slower in responding to sentences in the PHON condition than in the SEM condition, as seen in a significant main effect of Condition [F(1,49)=58.82; $p < 0.0001$]. There was no main effect of Length. The difference in reaction times between the two Conditions was greater for L2 speakers than for L1 speakers, seen in the significant interaction between Group x Condition [F(1,49)=4.86; $p < 0.05$]. No two-way interaction between any factor and the factor Length was observed in the reaction time data. Likewise, the three-way interaction between Group x Condition x Length did not reach significance.

Again it should be noted that reaction times are not a reflection of on-line sentence processing, as participants were told to wait until the end of the sentence before responding.

8.5 Discussion

The aim of this behavioral study was to investigate the effects of sentence context on lexical selection in auditory language comprehension. Specifically, it was the goal of this study to explore whether sentence context effects on lexical selection differ between native and non-native speakers.

Two clear results can be taken from this behavioral experiment. First of all, non-native speakers were simply worse and slower at judging spoken sentence material than were native speakers. This is indicated most directly by the fact that non-native speakers made significantly more errors than natives, and secondly by the fact that non-native speakers answered more slowly than natives. This is both intuitively easy to accept, and has been shown in other studies looking at second language processing (i.e.: Frenck-Mestre, 2002; Heredia & Stewart, 2002; Heredia, 2003).

More interestingly, sentence context did have an effect on lexical selection within sentences in both groups of participants. Lexical selection is one of three basic processing functions described in the word recognition literature: When processing acoustically presented words (whether presented in isolation or within sentence context) several wordforms are thought first to be activated in a bottom-up, stimulus-driven manner (lexical access); activated wordforms then compete with one another, until one form is ultimately selected (lexical selection); and finally selected wordforms are integrated into their surrounding context (lexical integration) (i.e.: Zwitserlood, 1989; Jusczyk & Luce, 2002).

In the lexical access phase, multiple lexical entries are postulated to be activated on the basis of both semantic and phonological information. The influence of semantic information on lexical access has been shown in that the presentation of ambiguous words (i.e.: wordforms with more than one meaning, for example *bug* meaning either an insect or a hidden recording device) causes lexical-semantic information for all possible alternatives to be called up. In other words, upon hearing *bug,* listeners show a short term facilitation in the processing of both *insect* and *spy.* (Swinney, 1979). Therefore, a single wordform accesses multiple lexical-semantic entries. On the phonological level, it has been postulated that phonologically similar wordforms are accessed simultaneously. The Cohort Model, for example, postulates that all word forms sharing phonological properties of the target word are activated in a left-to-right manner until the target word's uniqueness point is reached (Marslen-Wilson, 1987, 1989). In this way the word *elephant* initially co-activates *elevator, eleven, elegant,* etc. until enough acoustic information has been provided for each possibility to be ruled out and ultimately for the target word to be selected. A different account of phonological effects on lexical access is provided by the Neighborhood Activation Model, which postulates that phonologically similar wordforms are co-activated with a target word, regardless of initial phonemes (Luce et al., 1995). The phonological similarity neighborhood of a word refers to a collection of words that sound similar to a given target word. For example the target word *mug* has phonological neighbors such as *mud* and *hug*. A word in the phonological neighborhood differing from the target word by just one phoneme is called a minimal pair.

The co-activation of multiple lexical entries related both semantically and phonologically to a given target word is thus postulated at the lexical access level by most word recognition theories (for a review see Jusczyk & Luce, 2002). Interactive and modular models disagree as to how a single word form wins the ensuing competition to ultimately achieve selection, however both theoretical sides agree with the fundamental concept of activation and competition between numerous possibilities. The current study made use of phonological neighborhoods to study the effects of sentence context on lexical selection. According to the Neighborhood Activation Model (Luce et al., 1995), phonological neighbors of a presented target word are co-accessed alongside the target word itself (i.e.: *mug-hug*). The stimuli presented in this study were designed in such a manner that the target word itself could not be integrated into the sentence context for semantic reasons. In other words, the target word was semantically anomalous within the given sentence context (SEM). In some cases, however, a close phonological neighbor of the target word could be integrated into sentence context (PHON) (for examples see Table 8.1). This last stimulus type made up our critical condition. Both native and non-native speakers more often judged PHON sentences to be semantically plausible, demonstrating that sentential context biased the process of lexical selection away from the actually presented critical word, and towards a semantically plausible, co-activated alternative. The current results give no insight into whether contextual information influences lexical selection in a modular or an interactive fashion, as no information as to the timescale of said influence is available. The current study simply shows that contextual information did indeed influence lexical selection in both groups of participants.

Interestingly, although the effect of sentence context could be seen in both the native and non-native groups, the difference between the number of errors made in the detection of pure semantic errors vs. those semantic errors with a phonologically related alternative was significantly greater for the non-native speakers. In other words although both groups more often judged PHON than SEM sentences to be correct, the difference in the number of errors made between the two conditions was far greater in the group of non-native participants as indicated by the significant interaction between Group and Condition in the performance data. This interaction was also reflected in the reaction time data. This demonstrates that non-native speakers were influenced by sentence context to a greater degree than were native speakers. Non-native speakers appear to rely less than native speakers on bottom-up, stimulus driven input (i.e.: the actually presented acoustic stimuli) and more on top-down contextual information to help in the parsing of sentences as a whole. Native speakers, more practiced in the perception of speech sounds in their native language, can rely more accurately on bottom-up stimulus-driven input, and rely to a lesser extent on sentential context to determine what has been said.

We postulate on the basis of these results that sentence context directly influences lexical selection in non-native speakers. Specifically, we suggest that non-native speakers hold multiple phonologically similar lexical items active until the sentence is completed and the most plausible alternative can be selected. However, an alternative explanation could be that words with phonologically relevant neighbors are simply more difficult to integrate into sentence context (as indexed additionally by the main effect of Condition even for native speakers) and that poorer performance reflects integration costs rather than problems with lexical selection. We approach this alternative hypothesis by looking at the effects of the sentence length manipulation. The experimental material comprised sentences of two different lengths (see examples in Table 8.1). Short sentences were constructed with only one NP, which cannot be integrated with the following verb form conceptually. For example, in the sentence *The building was caught*, the words *building* and *caught* cannot be integrated conceptually under normal circumstances. Long sentences, on the other hand, contain 2 NPs, one of which cannot be integrated into sentence context. Although there is only one unrelated NP in the sentence, this noun suffers integration difficulties in conjunction with two elements in the sentence: (1) the other NP, and (2) the verb form. In other words, in the sentence *The building was caught in the sea,* the word *building* cannot be integrated successfully with either *caught* or *sea*. Therefore, there is a single integration problem in short sentences, and a double integration problem in long sentences.

If the poorer performance of non-native speakers in the PHON condition were to reflect integration difficulties, then we would expect to see an interaction between sentence type and length, and subsequently a significant main effect of length in judging sentences in the PHON condition. An initial interaction between sentence condition and length does indeed reach significance in the performance data of non-native speakers, however post hoc analysis show no main effect of length in either sentence condition. The interaction is a reflection of two non-significant differences in the performance rates of L2 speakers in judging each of the sentence types (see Figure 8.2). The lack of any main effect of length for either sentence type within the L2 group is taken as evidence against the idea that the observed differences between L1 and L2 speakers reflect integration difficulties alone.

We return to the hypothesis that numerous phonologically similar lexical alternatives have been activated, and that non-native speakers maintain this set of alternatives over a longer period of time, while waiting for sentence context to aid in the ultimate selection of

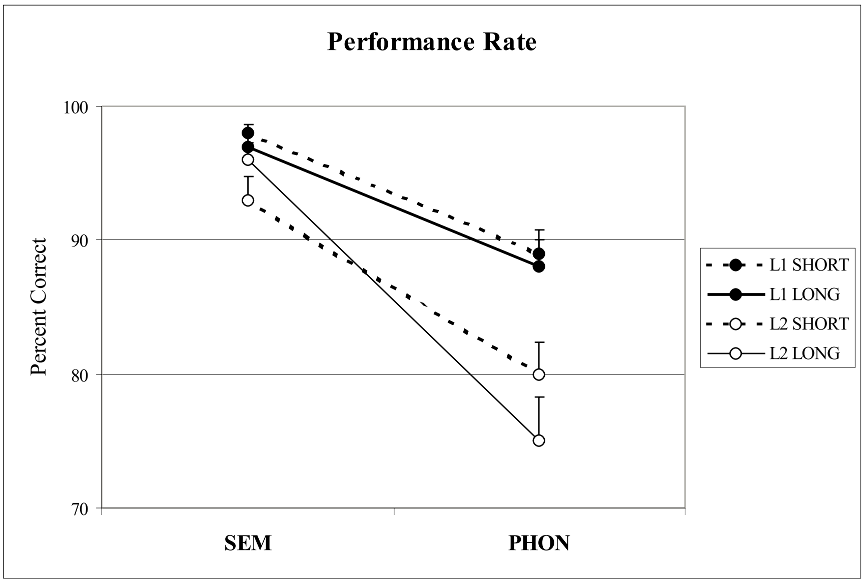

Figure 8.2: Performance rates and standard error for native (L1) and non-native (L2) speakers making judgments on sentences containing either a pure semantic error (SEM), or a semantic error with a semantically plausible phonological neighbor (PHON).

a single word. In discussing this idea, it is interesting to return to neuroimaging data on semantic processing.

The left IFG has been shown in numerous studies to be involved in semantic processing (for a review see Bookheimer, 2002). Exactly what aspect of semantic processing drives this activation remains an issue of debate, however two well-recognized theories are relevant to the current discussion. The selection hypothesis, proposed by Thompson-Schill and colleagues, suggests that left IFG activation is driven by ”the selection of information among competing alternatives from semantic memory”(Thompson-Schill et al., 1997). In other words, activation of left IFG was observed in response to the selection of a semantic feature from a set of competing alternatives: More possible alternatives lead to greater IFG activation. In this study it is emphasized that IFG activation reflects the degree of selection among competing alternatives, and not the amount of semantic retrieval *per se*. An alternate account can be found in the controlled semantic retrieval hypothesis, put forth by Wagner and colleagues (Wagner et al., 2001). Here it is suggested that a quantitatively greater amount of semantic retrieval (i.e.: the retrieval of 4 vs. 2 words) is the driving force behind semantically-related IFG activation. In an fMRI study these authors showed that the retrieval of quantitatively more words elicits increased activation in left IFG. Furthermore left IFG activation was modulated as a function of automaticity: Goal-directed, non-automatic behavior in relation to semantic retrieval elicited IFG activation, whereas automatic processes were not reflected in any increased IFG activation (Wagner et al., 2001).

The behavioral study presented here showed that non-native speakers use sentence contextual information to a greater degree than do native speakers in performing lexical selection in processing acoustically presented sentences. Because of this, it is hypothesized that phonologically similar words are kept activated as possible alternatives for selection for a longer period of time by non-native vs. native listeners. Lexical access of a greater set of alternatives is predicted to elicit increased levels of activation in the controlled semantic retrieval hypothesis (Wagner et al., 2001). Crucially, it is the goal-directed nature (i.e.: (1) the listeners awareness of the fact that a selection of one alternative must take place, coupled with (2) the top-down influence of sentence context on a lower level process) of the process behind lexical selection which drives IFG activation.

8.6 Conclusion

Non-native speakers are unable to rely solely on bottom-up acoustic information in word recognition. This is due to observed problems in categorization of phonemes in a second language. When listening to sentences, non-native speakers rely to greater extent on contextual information in making lexical selection concerning items within the sentence than do native speakers. The inability to make a lexical selection based on bottom-up cues alone leads to the prolonged activation of multiple phonological neighbors in non-native speakers. Sentence context aids in selecting one of these phonologically similar representations. The activation of multiple lexical items over a longer period of time is a possible explanation for the increased levels of IFG activation observed in other studies looking at processing of spoken language processing in non-native speakers.

Chapter 9

General Discussion

The dissertation presented here set out to investigate the processes underlying syntactic and semantic processing in spoken language comprehension in both native and non-native speakers of a language.

Experiment 1 attempted to identify cerebral regions selectively responsible for the processing of sentential syntactic structure and sentential semantic information. In this study syntactic processing was dissociated from semantic processing by way of a well-established violation paradigm. An event-related analysis of the BOLD response of native German speakers to correct and incorrect sentences was performed. Syntactic anomalies elicited increased activation in the mid to anterior superior temporal gyrus (STG). Semantic anomalies elicited increased levels of activation in anterior to posterior superior portions of the inferior frontal gyrus (IFG).

Experiment 2 investigated to what degree results obtained in Experiment 1 could be generalized across languages. The central research question here was whether native speakers of two different languages demonstrate comparable cerebral activity when presented with spoken sentence stimuli in their respective native languages. To this end native speakers of Russian were presented with similar sentence material to those used in Experiment 1 in the Russian language. The results showed increased levels of activation in response to syntactic and to semantic anomalies, which were comparable to those seen in Experiment 1. Syntactic anomalies elicited increased activation in mid STG; Semantic anomalies elicited activation in anterior IFG (BA45).

Experiment 3 investigated differences in the processing syntactic and semantic information in sentences by native (L1) vs. non-native (L2) speakers of a language. To this end the sentence stimuli from Experiment 1 were presented to a group of highly-proficient non-native speakers of German (native speakers of Russian). The question of interest in this study was whether the same pattern of cerebral activation seen in native speakers (Experiments 1 and 2) underlies processing of a non-native language. A within L2-subjects analysis of differences between the anomalous sentence conditions and correct conditions showed (1) no regions of differential activation in response to syntactic anomalies vs. correct sentences, and (2) increased levels of activation in response to semantic anomalies in left IFG. A between subjects analysis of results from this experiment and experiment 1 (L1 vs. L2) showed increased activation in L1 speakers for language processing per se in particular in the left STG. Non-native speakers, on the other hand, showed increased levels of activation in a network of cerebral regions comprising left IFG, left intraparietal sulcus (IPS) and the head of the caudate nucleus bilaterally.

In **Experiment 4** the role of verbal working memory in non-native language processing was investigated. Specifically it is suggested that verbal working memory may serve as a compensatory mechanism for non-native speakers to overcome the lack of automatic processing steps seen in native speakers. The results showed a dramatic decrease in accuracy when non-native speakers were asked to judge the grammaticality of sentences while conducting an articulatory suppression task.

In **Experiment 5** the effects of sentence context on lexical selection in non-native language processing was investigated. Non-native speakers demonstrated evidence of maintaining multiple lexical alternatives open until sentence context allows for one alternative to be integrated into sentence context.

In the following chapter the implications of these results on theoretical and other empirical studies is discussed. First, the implications of the data obtained from native speakers alone on neurocognitive models of language processing is addressed. Secondly, the attempted localization of syntactic and semantic processing in the brain is discussed, and the empirical evidence from Experiments 1 and 2 are discussed against a background of existing literature. Thirdly, theories concerning the processing of native and non-native sentence comprehension are addressed, and empirical data from Experiment 3 is fit into this framework. Lastly, it is suggested that vWM may greatly support L2 spoken language comprehension. The putative role of vWM in language processing is addressed, and differences in the manner in which vWM might support L1 vs. L2 language processing are pointed out.

9.1 Neurocognitive Models of Language Processing

The neuroimaging data presented in this thesis is in holding with dual-systems models arguing for a dissociation between syntactic and semantic processing in sentence comprehension (i.e.: Friederici, 2002; Ullman, 2004; Grodzinsky, 2000). In all three neuroimaging studies (Experiments 1-3) a clear distinction could be drawn between cerebral regions selectively involved in the processing of syntactic information and those involved in the processing of semantic information.

Between dual-systems models it remains a matter of debate how the distinction between different domains is realized on the brain level. The neurocognitive model of auditory sentence processing (Friederici, 2002) localizes syntactic and semantic processing within two different fronto-temporal cortical networks: Early syntactic processing is suggested to depend on anterior superior temporal gyrus (STG) and inferior frontal gyrus (IFG; BA44), whereas the processing of semantic information relies on middle temporal gyrus (MTG), medial temporal cortex (MTL) and anterior portions of IFG (BA 45/47). The neuroanatomical specifications are based on empirical evidence coming from various neuroimaging studies. The Declarative/Procedural Model (Ullman, 2001b, 2004) identifies specific neural regions to be particularly relevant in processing syntactic vs. semantic information by drawing a parallel between these linguistic domains and two frequently investigated memory systems. Specifically, syntax is postulated to tap into the procedural memory system, responsible for the learning of new skills and for controlling well-established motor and cognitive skills. The procedural memory system is 'rooted in portions of the frontal cortex, the basal ganglia, parietal cortex and the dentate nucleus of the cerebellum' (pg. 718). Syntax processing in the Declarative/Procedural model is thought to rely primarily on frontal cortex and structures of the basal ganglia. Semantic information, on the other hand, is suggested to draw on resources of the declarative memory system. This system supports the long term storage of factual information and episodic knowledge. Declarative memory, and thus semantic processing, is postulated to reside in the medial temporal lobes and the anterior prefrontal cortex.

The neurofunctional data presented in this thesis can neither verify nor refute either of these two models. While models of language processing attempt to explain language processing in general, on the empirical level of single studies, clearly only portions of the whole can be selectively investigated. The general results are, as was pointed out previously, in accordance with both models in so far as both postulate a functional and anatomical distinction between processing of syntactic information and processing of semantic information. While each model makes different predictions as to the overall network underlying syntactic and semantic processing, they do not differ from one another fundamentally or necessarily contradict one another. The neurocognitive model of auditory sentence comprehension is an empirically-driven model, which was developed initially on the basis of electrophysiological studies. The Declarative/Procedural model is a theoretical comparison between two larger cognitive domains, which is supported by several empirical studies. The empirical data collected in the framework of this thesis would have been better predicted by the neurocognitive model of auditory sentence comprehension, however there was no direct attempt made in this thesis to investigate the relation between memory and sentence processing, and the results do not directly contradict other dual-system models. A slightly different focus or task may have produced different results. Such issues are topic of future research. In the following the results will be discussed against a background of existing empirical evidence, and the agreement of certain data with various models will be pointed out when relevant.

In Experiments 1 and 2 an increased involvement of mid to anterior STG was observed in L1 speakers in response to syntactic (phrase structure) anomalies. This is in holding with the neurocognitive model of auditory sentence comprehension, as well as other neuroimaging data in which a special role of anterior STG (aSTG) is argued to support morphosyntactic and phrase structure processing in sentences (Dronkers et al., 1992; Bavelier et al., 1997; Meyer et al., 2000; Humphries et al., 2001; Friederici, 2002; Friederici et al., 2003; Rüschemeyer et al., in press). It is also in accordance with several electrophysiological studies, in which the neural generator of the ELAN, thought to reflect detection of phrase structure violations, is postulated to be seated in anterior STG (Knösche et al., 1999; Friederici et al., 2000b). It should be pointed out that the results of Experiments 1 and 2 are not suggested to depict exactly those processes captured in electrophysiological studies– the timecourse information of EEG and fMRI being grossly different from one another. However, the convergence of evidence from multiple methods, all pointing to aSTG as a locus of sentential syntactic information suggests that different methods measure related processes of language comprehension.

The activation observed in Experiments 1 and 2 within STG had two local foci– one within aSTG and one in mid STG (mSTG), lateral to Heschl's Gyrus. Because of the proximity of mSTG to primary auditory cortex, it must be discussed to what extent increased activity in this region might be a by-product of low level auditory processing. Specifically, syntactically anomalous sentences eliciting mSTG activation were one word longer than correct baseline sentences (see examples). However there is preliminary evidence from a visual study of language comprehension using the same sentence stimuli (in other words, a language study with no auditory input), in which comparable activation of mSTG is again observed in response to syntactic anomalies (Rüschemeyer & Friederici, submitted). Mid STG activation in this study can clearly not result from acoustic input. Furthermore, the results of Experiment 3, in which changes in the BOLD-response of L2 speakers to the different sentence conditions were recorded, show no such dissociation in mSTG. If mSTG activation reflected low level acoustic processing alone, the pattern of activation would not be expected to differ as a function of native language. Thus, the mSTG activation along with the aSTG activation observed in L1 speakers in response to syntactically anomalous sentences is suggested to reflect incompatibility between the incoming speech signal and the participant's phrase structure expectancy.

The results from Experiments 1 and 2 diverge from the models as well as a number of empirical studies arguing for a crucial role of inferior frontal cortex, in particular Broca's Area, in syntax processing (i.e.: Just et al., 1996; Caplan et al., 1998, 1999; Caplan, 2001; Grodzinsky, 2000; Wartenburger et al., 2004). The current results diverge in that no specific involvement of IFG is detected in response to syntactic processing. However, as Embick and Poeppel point out in a review of neuroimaging studies investigating syntactic processing, the terms 'syntax' as well as 'Broca's Area' are used to encompass quite a diverse set of things (Embick & Poeppel, 2003). Studies investigating syntactic complexity, for example, certainly reflect a different type of processing than studies using violation paradigms (see also Friederici, 2004). In fact, even within violation paradigms, good evidence exists for a neurophysiological distinction between different syntactic violation types (Friederici & Meyer, 2004). The fact is, those studies which report a special involvement of Broca's Area for syntactic processing have usually looked at either grammatical transformations (Ben-Shachar et al., 2003) or grammatical complexity issues (Stromswold et al., 1996; Caplan et al., 1998, 1999; Caplan, 2001; Just et al., 1996), or have otherwise required additional processing such as reparation of violations (Meyer et al., 2000). The results of Experiments 1 and 2, in their failure to detect substantial IFG activation specifically in response to syntactic violations in comparison to correct sentences, are actually in holding with a substantial amount of literature (Kuperberg et al., 2000; Meyer et al., 2000; Ni et al., 2000).

This is not to say that Broca's area plays no role in the processing of anything but complexity in sentences. The failure to detect any activation of IFG in Experiments 1 and 2 in response to syntactic anomalies is certainly due at least in part to the nature of the direct comparisons drawn: In all experiments in this thesis, syntactic processing was captured in a direct comparison between the brain's response to sentences containing a phrase structure violation vs. the brain's response to well-formed sentences. This contrast obviously does not capture a comprehensive syntax-processing network, as syntax processing takes place in both conditions. Therefore any regions seen to be equally active for both the processing of syntactically anomalous and correct sentences are not visible in such a contrast. The fact that both sentence types elicited a change in the BOLD-response within IFG can be seen upon inspection of the timecourse information depicted in Figure 9.1. If the BOLD-response in these conditions is compared to a BOLD-response to a resting baseline, left IFG (pars opercularis) activation is seen for all conditions.

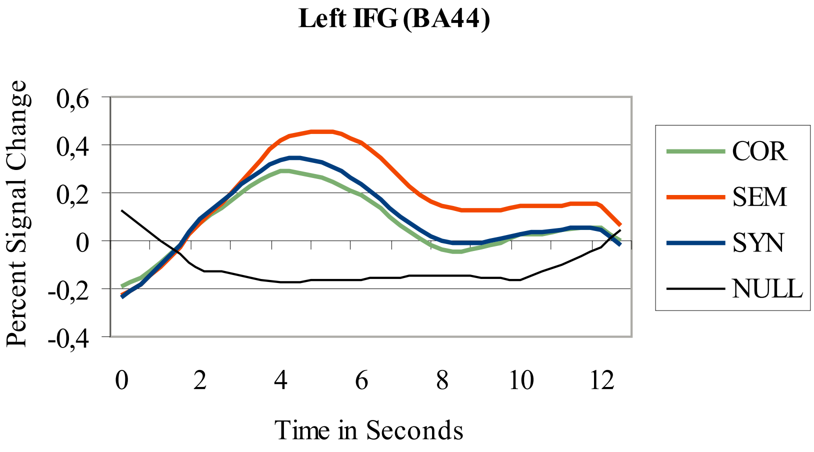

Figure 9.1: Percent signal change over time for native German speakers listening to correct (COR), syntactically incorrect (SYN) and semantically incorrect (SEM) sentences compared to the resting baseline (NULL).

As to the processing of semantic information in sentences: The neuroimaging results presented in Experiments 1 and 2 provide further evidence for the existence of a fronto-temporal network underlying what several authors have referred to as goal-directed, strategic semantic processing(review see Bookheimer, 2002). This is in direct accordance with the neuroanatomical model of auditory sentence comprehension, and only partially supported by the Declarative/Procedural model. Specifically, both models suggest that portions of prefrontal cortex are responsible for aiding in the strategic retrieval of semantic information. This is supported by empirical evidence from a number of studies (Thompson-Schill et al., 1997; Wagner et al., 2001; Bookheimer, 2002) as well as the neuroimaging data from Experiments 1-3. It is of particular interest that non-native speakers appear to combat problems in the retrieval of semantic information in a similar fashion to that seen in native speakers (Experiment 3). This suggests that the processing of semantic information is conducted along similar lines in native and non-native speakers, and will be discussed further below.

In temporal cortex a small region of activation in the posterior superior temporal sulcus (STS) and middle temporal gyrus (MTG) was observed to be more activated by semantically anomalous sentences than correct sentences. Posterior STS/MTG has been suggested to support the integration of information from various linguistic domains in order to enable final sentence interpretation (Friederici et al., 2003). However, in such an account posterior STS/MTG involvement would be predicted for syntactic anomalies as well. While the results of Experiment 1 do not show this reliably, it was pointed out at length in the discussion of Experiment 1 that a small number of voxels do actually pass a significant threshold of activation in response to syntactic anomalies, and that timecourse information shows a reliable response to syntactic anomalies in pSTG/MTG. Therefore the possibility that this portion of cortex is involved in final sentence integration of information from syntactic as well as semantic domains should not be disregarded. Modulation of activation within medial temporal cortex was not observed in Experiments 1 or 2, however this is the result of failure to capture these areas in the functional measurements. In order to keep acoustic interference from the scanner to a minimum, only eight slices were measured in functional measurements in Exp. 1 and ten slices in Exp. 2. In order to reliably capture signal from both IFG and posterior STS, the slices were situated in such a manner that medial temporal lobe (MTL) was not measured in most participants. Regrettably the question of MTL activation can therefore not be resolved with the present data, but deserves further investigation in studies focusing on the functional anatomy of temporal cortex. It is hypothesized that studies including measurement of MTL would observe increased activation of this region in response to semantic anomalies.

Importantly, the neuroanatomical substrates of language processing are not assumed to be unique to any one spoken language, although the processing of specific surface features of different languages (i.e.: orthography) has been argued to have an effect on processing strategies (Paulesu et al., 2000; Tan et al., 2003). Activations in the aforementioned classical language areas as a function of higher level linguistic processing (i.e., processing of semantic versus syntactic features) have been observed not only for English and German, but also for Italian (Moro et al., 2001) and Japanese (Suzuki & Sakai, 2003). Experiment 2 extends these results to include Russian, and simultaneously shows that comparable linguistic stimuli in two typologically different languages (Russian and German) elicit comparable responses within the brain.

9.2 Native vs. Non-native Sentence Processing

The second main goal of this thesis was to investigate differences in the neural networks underlying the processing of a native vs. a non-native language. The L2 speakers in these studies were always late learners of German (having learned German after the age of 15), who nevertheless had a high degree of proficiency and high levels of L2 exposure due to their work/education environment.

The fact that all participants were late learners of their second language is important, as age of acquisition (AoA) has been shown to correlate with L2 proficiency and processing. Importantly, effects of AoA have been shown to differ across linguistic domains, syntactic processing, for example, showing a greater effect of AoA than semantic processing. Domain specific effects of AoA have been recorded behaviorally (Flege et al., 1999; Meador et al., 2000), electrophysiologically (Weber-Fox & Neville, 1996) and using neuroimaging (Kim et al., 1997; Perani et al., 1998). The neuroimaging results obtained in Experiment 3 are in full accordance with data showing that late learners of a second language differ dramatically from native speakers in their processing of syntactic information, but not in the processing of semantic information. In the following two sections this will be addressed in detail.

9.2.1 Syntax Processing

While native speakers demonstrate significantly more involvement of bilateral (and particularly left) STG in response to phrase structure violations compared to correct sentences, non-native speakers show no regions of differential activation in response to the same two conditions. The results indicate that words violating phrase structure expectancy are processed differently than words respecting phrase structure by native speakers but not by non-native speakers of a language. STG activation was interpreted in Experiments 1 and 2 to reflect detection of phrase structure violations based on incompatible word category information. The omission of this processing difference in non-natives could be interpreted to indicate that (1) non-natives do not build on-line phrase structure expectancies in order to parse spoken speech, or (2) that word category information available at a very early stage of lexical processing to native speakers, is not available to non-natives in the same timeframe. Either way, phrase structure violations cannot be detected at the onset of the critical word by non-natives.

Both interpretations are entirely in holding with the results of electrophysiological studies, in which non-native speakers, in contrast to natives, showed no early response to phrase structure violations (Hahne, 2001; Kubota et al., 2003, 2004). In other words, at least within an early and automatic phase of processing, non-native speakers showed no evidence of a different response to syntactically congruent and syntactically incongruent wordforms. Native speakers, on the other hand, did show a differential response, suggesting that automatic detection of an incongruent word category may aid in a very fast and efficient parsing of sentence structure (Friederici, 2002).

Importantly, native speakers of Russian do show a dissociation between phrase structure violations and correct sentences in Russian, as seen in Experiment 2. This indicates that the strategy underlying native language processing in general is the same between native speakers of German and Russian in dealing with phrase structure violations in their respective native languages. Therefore, it is not that native speakers of Russian simply process language per se differently, rather it is the 'non-nativeness' of German which leads them to use different strategies.

9.2.2 Semantic Processing

The results of Experiment 3 show that the brain response of non-native speakers to semantic anomalies in sentences is quite similar to that of natives, although not identical. Non-native participants in Experiment 3 showed an increased modulation of the BOLD response in response to semantic anomalies in left IFG (BA44). Both groups of natives in Experiments 1 and 2 showed increased activation in the left IFG in response to semantic anomalies, however in a further anterior portion of IFG (BA45/47). Experiment 1 was able to capture more functional information, as the group of participants was more than twice as large as that reported in Experiment 2. The results of Experiment 1 show that IFG activation spread from anterior portions (BA45/47) through to the superior posterior IFG (BA44/6). In other words, although a peak of activation in response to semantic anomalies appears to be located in anterior IFG (BA45), reliable activation is detected throughout BA44, comparable to that seen in non-natives.

The left IFG has been cited in several studies looking at strategic semantic retrieval (for a review see Bookheimer, 2002). What precisely is behind 'strategic' remains to be clarified– some researchers have argued that IFG activation reflects difficulty of retrieval processes (Thompson-Schill et al., 1997), while others have argued that it reflects amount of retrieval (Wagner et al., 2001). This dissertation did not attempt to distinguish between different types of retrieval. Fact is that semantic anomalies elicited increased activation in comparable regions within particularly the left IFG in native speakers of two different languages (Experiments 1 and 2) and non-native speakers (Experiment 3).

Again this is in holding with electrophysiological studies, demonstrating similar results for non-native and native speakers. Specifically, non-native speakers have been shown to display an N400 in relation to semantically incongruent words (Weber-Fox & Neville, 1996; Hahne, 2001; Hahne & Friederici, 2001). As this effect is very robust in native speakers, this suggests that non-native speakers processes semantic anomalies along similar lines as seen in natives.

9.2.3 General Comprehension

Non-native speakers showed more activation than native speakers in a fronto-parietal-basal-ganglia network in language processing per se (Experiment 3). This network involved left IFG, left intraparietal sulcus and the bilateral caudate nucleus. Across all experimental conditions (regardless of whether sentences were correct or incorrect), non-native speakers showed a strong involvement of these three areas. A similar network comprising left IFG, left inferior parietal lobule (BA40) and caudate nucleus has been implicated in studies of verbal working memory (Henson, 2001). In particular inferior parietal lobule is thought to house a short term phonological store, while caudate nucleus and IFG are thought to support covert rehearsal and retrieval via the articulatory loop (Baddeley, 1997; Henson, 2001). It is therefore suggested on the basis of activations observed in Experiment 3 that non-native speakers draw on verbal working memory resources to aid in sentence comprehension. To what end L2 speakers rely on WM cannot be determined based on the neuroimaging data alone. This question was addressed in two further behavioral studies, and will be discussed in the greater context of WM and language processing in the following sections.

Selected brain region were, however, also shown to be more activated in native than in non-native speakers. Specifically, native speakers show higher levels of activation in the bilateral STG, most predominantly in the left hemisphere. The role of STG in language processing has already been discussed at some length. Here it may suffice to say that although the precise function of STG in auditory language processing remains unclear, a number of studies have shown that it is involved in the comprehension of spoken sentences as opposed to spoken words or word lists. For this reason it is argued that left STG supports the integration of incoming words into established phrase structure on the basis of functional elements. This process is conducted in a fast, continuous and automatic manner (Hahne & Friederici, 1999). It is proposed that upon encountering the head element of a phrase (in the case of the experimental stimuli used here the preposition) an expectancy as to the required phrase-completing complement (here a noun) is constructed. This expectancy is violated upon presentation of a word belonging to a category that cannot be integrated into the expected phrasal structure (in this case a verb participle). Such violations of word category are easily and quickly detected by native speakers (reflected in the ELAN), the generator of which has previously been proposed to be situated in STG (Knösche et al., 1999; Friederici et al., 2000b). Non-native speakers, on the other hand, do not detect word category violations on the same timescale as natives (no ELAN). This may be due to an inability to make syntactic predictions (Kubota et al., 2003, 2004), or may be due to an inability to quickly access and utilize word category information. Again, the neuroimaging data from Experiment

3 alone cannot distinguish between these two alternatives. However, it is suggested that the greater level of activation observed in STG in natives, which was recorded at the onset of the critical word, reflects the detection of phrase structure violations based on word category information, a process hindered in non-native speakers.

The neurocognitive model of auditory sentence comprehension has not been explicitly extended to include L2 speakers, however the neuroimaging data presented in Experiment 3 can be explained well based on the putative language functions ascribed to STG, IFG and the basal ganglia in this model. The results are not in accordance with specific predictions regarding the neural correlates of L2 processing made by the Declarative/Procedural (DP) model (Ullman, 2001a). The DP model suggests that L2 speakers compensate for processing difficulties in the syntactic domain by recruiting additional semantic processing resources. In other words, it is postulated that non-native speakers rely heavily on semantic processing in order to compensate for syntactic weaknesses. Consequently, the DP model predicts that L2 speakers will show a decrease of activation in those areas thought to be involved in syntactic processing in native speakers (i.e.: most notably the frontal cortex and basal ganglia) and an increase in those areas underlying semantic processing (temporal lobe and MTL). In fact the results of Experiment 3 show just the opposite. Non-native speakers show increased activation in precisely IFG and structures of the basal ganglia, while native speakers show a greater involvement of temporal cortex.

9.3 Verbal Working Memory as an L2 Sentence Processing Strategy

The neuroimaging results from Experiment 3 showed a network of cerebral areas typically involved in verbal WM to underlie specifically non-native language processing. The role of vWM in second language processing has previously been restricted to second language learning of new vocabulary, however the results of Experiments 4 and 5 demonstrate that WM may underlie multiple aspects of second language comprehension, including compensating for deficits in on-line syntactic structure building and phoneme discrimination.

9.3.1 Phrase Structure

It has been shown that L2 speakers do not detect phrase structure violations based on word category violations in the same automatic manner as L1 speakers. Support for this theory comes from electrophysiological studies (Hahne, 2001; Hahne & Friederici, 2001; Kubota et al., 2003, 2004; Mueller, in pressb), and from the neuroimaging results presented in this thesis (Exp. 3). Compensation for this shortcoming may make use of the short term verbal

WM system. Why? In order to discuss this the role of vWM in native language processing must first be illustrated.

Verbal WM has been suggested to support L1 sentence processing in a number of ways: (1) In facilitating the resolution of locally ambiguous syntactic structures (Just & Carpenter, 1992); (2) in facilitating the integration of information from multiple linguistic domains (Just & Carpenter, 1992); (3) by supporting the on-line processing of complex syntactic structure (Caplan & Waters, 1999), and specifically by keeping track of obligatory syntactic requirements between heads and complements separated by filler-gap distances (Gibson, 1998; Fiebach et al., 2001, 2002b). Particularly this last suggestion is relevant in the current discussion of phrase structure processing strategies. Specifically, it has been suggested that vWM is used by native speakers to maintain syntactic dependencies until all required slots in the structure have been filled (Gibson, 1998). The only phrasal type excluded from memory costs is the verbal phrase, as this is consistently required in all sentences (Gibson, 1998). Importantly, the costs incurred on WM are suggested to be influenced by locality, meaning that the longer a dependency is kept unfilled, the more WM resources will be drawn upon. In the sentences presented in this experiment, the head of the prepositional phrase in syntactically incorrect sentences, should alert the parser to watch for a complementary noun (*Die Gans wurde im ...*). The following word, however, is a verb participle (*gefüttert*), which cannot be fit into the phrasal structure initiated by the prepositional head. Native speakers detect the word category of the participle *gefüttert*, judge this to be incompatible with the initiated phrasal structure and immediately judge sentences to be incorrect (ELAN: Friederici, 2002). No severe costs are incurred on WM, as the sentence structure is deemed irreparable one word after the initiated PP.

As discussed previously, non-native speakers do not detect phrase structure violations based on word category violations on the same timescale as natives. Until now I have discussed differences between the response of L1 and L2 speakers to the detection of phrase structure violations as resulting from either (1) a failure of L2 speakers to build phrase structure expectancies, or (2) a failure of L2 speakers to make use of word category information in the same manner as L1 speakers. Both interpretations can be made on the basis of the empirical data available. What possible strategies could L2 speakers use, however to compensate for these deficits? If processing differences result from the failure of L2 speakers to build phrase structure expectancies on-line, it could be postulated that L2 speakers wait until the end of a given sentence to begin parsing. This would entail the continuous storage of perceived words until a given point at which reconstruction could begin. The maintenance of multiple wordforms over time has been shown to rely on WM (Miyake et al., 1994). After a controlled reanalysis of syntactic structure, L2 speakers would be capable of making grammaticality judgments. This account is rather difficult to accept, as (1) it is not clear what the magic point for L2 speaker to begin parsing would be (end of the sentence, end of the phrase?), and (2) it would imply that non-native speakers have no means of comprehending speech before the end of a phrase or sentence is reached. This is intuitively rather implausible.

The second suggestion, that L2 speakers are delayed in their access/utilization of word category information, is easier to accept. In this account, non-native speakers are alerted to phrase structure dependencies upon encountering the prepositional head in syntactically anomalous sentences in a manner analogous to that seen in natives. As in the case of L1 speakers, the parser is alerted to wait for a complementary noun. However, if L2 speakers are unable to use word category information about the participle quickly to detect phrase structure incongruency (reflected in the missing ELAN), then WM must maintain the phrase structure expectancy for a longer time before detecting a violation. This additional time over which phrase structure expectancy is maintained incurs additional WM costs for L2 speakers in comparison to L1 speakers.

The results of Experiment 4 show that making vWM inaccessible by means of articulatory suppression (AS) causes interference selectively with the processing of L2 syntactic structure (as measured by the detection of phrase structure violations). This is hypothesized by the argument laid out above: (1) L1 speakers show no effect of WM interference, as they have no great need to draw on WM resources (no open head dependencies), (2) L2 speakers show no interference of AS on the comprehension of simple sentences, which require the construction of no syntactic expectancies beyond those related directly to the verb phrase, however a massive interference of AS on the comprehension of sentences containing an additional phrase structure. Resolution of the head-complement dependency is sought in L2 speakers for a longer period of time than L1 speakers, because L2 speakers cannot determine word category information as quickly as native speakers.

Several problems persist with this interpretation: (1) Did AS really affect the function of vWM, or was the interference observed in L2 speakers due to unintentional perceptual interference? It has been proposed, for example, that neural regions supporting the perception of speech are shared with those supporting speech production (Motor Theory of Speech Perception: Liberman et al., 1967). Therefore, it is possible that the overt articulation of speech interfered with L2 speakers perceptual abilities. This was ruled out based on the fact that such an interference would be expected in all sentence conditions, and not selectively for the perception of syntactic errors. A further problem of perceptual interference arises along morphosyntactic lines: The AS task caused participants not only to produce irrelevant speech, but also to unavoidably perceive the word they produced. It was therefore possible that the perception of the irrelevant speech stimuli interfered with language comprehension. In particular the irrelevant word belonged to the word category missing in syntactically incorrect sentences. Therefore, it was possible that AS interfered with the perception of phrase structure violations due to the morphosyntactic congruency of the irrelevant word with the given phrase structure. This was ruled out in Exp. 4B, in which participants conducted the same experiment while an outside observer produced the irrelevant word. The detection of phrase structure anomalies did not differ from detection of the same structures in the scanner (in the absence of any speech interference). This demonstrated that the perception of the congruent word category per se did not interfere with the detection of phrase structure violations.

A second point of contention surrounds the neuroimaging data. If L2 speakers rely more on WM in the syntactically anomalous condition due to the additional phrase structure initiated in these sentences, then such a difference should be observed on the neural level in the within L2 subjects contrast between syntactically anomalous and correct sentences. This was not the case: In fact no regions of differential activation were observed between these conditions. Three points must be made here: (1) The interpretation of the null-result in the contrast between syntactically anomalous sentences and correct sentences must be treated with caution. The failure to detect increased activation in the WM circuitry in response to syntactically incorrect sentences in comparison to correct sentences may be an issue of power. Such activation might be detected with more trials or more participants. (2) The modulation of the BOLD-response in co-occurrence with the onset of the critical word may have led to such a null effect. It is possible that a slightly delayed modulation of the BOLD-response (i.e.: a sentence final modulation) would provide different results. This was not done in order to avoid the inclusion of activation related to sentence-final wrap-up effects and premotor planning of the sentence acceptability task. Additional experiments could be conducted however, in which the critical word is not simultaneously the sentence-final word. With such sentence material a temporal shift of BOLD modulation could potentially give more insight into how non-natives detect the syntactic anomaly. (3) Although Gibson (1998) suggests that prediction of the predicate is WM cost-free in native speakers, it could be speculated whether this is true for non-natives. If not, WM might actually be directly involved in the processing of syntactic structure in all sentence conditions. This would explain the lack of difference in BOLD-response in response to syntactically anomalous vs. correct sentences in the within-group contrast, as well as the differences in BOLD-response across conditions observed in the between subjects contrasts. While this is not the direction in which I argued previously, the possibility must be left open for future research. The behavioral results of Exp. 4, showing a selective decline in accuracy rates for the detection of syntactic anomalies, can be explained in such an account by accepting the theoretical idea postulated by Ullman regarding L2 use of semantic information to compensate for syntactic shortcomings (Ullman, 2001a): Specifically, L2 speakers are postulated to compensate for deficits in syntactic processing with semantic knowledge. In judging correct and semantically incorrect sentences in the experiments presented here, a judgment of acceptability based on semantic information alone leads to a correct answer. However, in the case of syntactically incorrect sentences, all words are parsimonious on the conceptual level. Relying on semantic information alone therefore causes L2 speakers to more often judge syntactically anomalous sentences as correct, explaining the drastic reduction in accuracy rates. This could be tested by presenting participants with an additional experimental condition made up of sentences containing both a syntactic and a semantic error, for example *Der Vulkan wurde im gegessen*. L2 participants instructed to respond to both semantic and syntactic anomalies should perform well on this task. L2 participants instructed to respond only to syntactic errors, on the other hand, should continue to perform poorly.

9.3.2 Lexical Selection

Verbal working memory may, however, also affect L2 speakers in their comprehension of spoken language on the lexical level rather than the syntactic level. In native speakers the maintenance of multiple word forms over time has been shown to depend on WM (Miyake et al., 1994). The behavioral study presented in Chapter 8 provided evidence that non-native speakers maintain multiple lexical alternatives over the course of an entire sentence, before making use of sentence context to guide lexical selection. Both the maintenance of multiple lexical items *per se*, as well as the maintenance of items *over time* would predict an involvement of WM.

The results of Experiment 5 do not directly show that multiple items are continuously accessed, only that the final selection of a word presented early in the sentence can be altered by later contextual information. This strongly suggests that the initially accessed phonological neighbors remain in a state of activation over time, however it is also possible that they are reactivated upon reaching the end of the sentence. This leaves room for future research, in which timecourse information concerning lexical access and the maintenance of accessed words must be investigated. Specifically, cross-modal priming studies along the lines of those conducted by Swinney (Swinney, 1979) could provide insight into how initially activated phonological neighbors are maintained over time.

9.4 Conclusions and Open Questions

(1) There is good evidence for the fact that syntactic and semantic information in sentences is processed by the brain in distinct cerebral areas. While this conclusion is not new in and of itself, additional evidence was provided for a specific role of the left anterior to mid STG in the processing of syntactic phrase structure information, and a specific role of the left IFG in processing semantic information. Several questions clearly remain open: First, does the STG support syntactic processing in general or is it specifically involved in the detection of phrase structure violations? Along similar lines, does STG activation reflect the detected mismatch in word category information in the sentences presented to participants here, or does it reflect increased efforts in attempting to repair the mismatch condition, for example by building a new phrase structure? These are interesting issues for further research.

Furthermore similar cerebral regions were seen to be activated in response to similarly constructed sentence materials in native speakers of two typologically different languages. While language processing in the brain has been investigated in different languages before, this was the first study of auditory sentence comprehension to be conducted comparing comparable controlled linguistic stimuli across languages. The results speak for general language processing strategies, which are not tied to a specific language. The results, however, fall short of being able to argue for a universality in language processing across all languages. The investigation of native speakers of two non Indo-European languages would, for example, be of interest. Finding comparable controlled linguistic stimuli between such language pairs might present a challenge, but the results would provide more insight into the general organization of language in the human brain.

(2) Non-native speakers of a language processes syntactic information differently than native speakers; meanwhile non-native speakers appear to rely on similar cortical networks to process semantic information. This was shown for non-native speakers responding to phrase structure violations, however the following questions remain unanswered: Can this be said for the processing of other syntactic processes? How do non-natives deal with syntactic structures which are not represented in their own language; and to what degree does non-native processing of syntactic structure fall back on semantic processing? Studies including modulation of the BOLD-response in medial temporal cortex might give more insight into this last question.

(3) Non-native speakers, comprehending spoken sentences, show greater levels of activation than native speakers in several cerebral regions including the left IFG, the left IPS and bilateral structures of the basal ganglia. Such a network has been suggested to support processes of verbal working memory. Therefore, the anatomically motivated proposal was made that non-native speakers compensate for shortcomings in automatic language processing abilities by relying on verbal working memory.

While the empirical data support this initially, many studies must be conducted to test the validity of this proposal. First of all, it is not clear from the results of the behavioral studies presented in this dissertation to what extent verbal working memory affects specific domains of non-native language processing. Evidence was provided showing that aspects of both syntactic and semantic processing may draw on working memory resources. These two domains can be united, when one considers that detection of the phrase structure under investigation here relied on access to word category information. Delayed lexical selection in L2 speakers may delay access to word category information, which would result in interference in processing phrase structure. Interesting further points of study certainly include investigations of lexical selection in L2 speakers as well as the processing of other syntactic violation types.

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The Processing of Lexical-Semantic and Syntactic Information in Spoken Sentences:
Neuroimaging and Behavioral Studies of Native and Non-native Speakers
Universität Leipzig
144 pages, 181 references, 11 Figures, 16 Tables

Paper The dissertation presented here had two primary goals: (1) to investigate the neural substrates of syntactic vs. semantic processing in spoken sentence comprehension, and (2) to compare the cerebral organization of language in the brain between native (L1) and non-native (L2) speakers. Syntactic and semantic processing were dissociated from one another by means of a violation paradigm. Participants in three neuroimgaing studies listened to correct, syntactically incorrect and semantically incorrect sentences while changes in the hemodynamic response (BOLD-response) were recorded using functional magnetic resonance imaging (fMRI).

Within each group of participants, sentential syntactic processing was captured in the direct comparison between the BOLD-response to phrase structure anomalies as compared to correct sentences. Semantic processing was likewise captured in the direct comparison between the BOLD-response to semantically anomalous sentences and correct sentences. Differences in the language processing strategies implemented by each group was characterized by a between group analysis of the neural response to each experimental stimulus type.

The neuroimaging results indicate that syntactic and semantic processing are distinguishable from one another on the brain level in native speakers. In non-native speakers activation underlying syntactic processing differed from that observed in the native speakers. Non-native processing of semantic information, on the other hand, relied on similar cortical areas as seen in natives. Language processing *per se* elicited increased levels of activation in a frontostriatal loop in non-native speakers in comparison to native speakers. Two further behavioral studies were conducted, in which an enhanced role of verbal working memory is suggested as a compensatory strategy for non-native speakers in comprehending spoken language.

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