From acoustic to language processing: development of neuronal mechanisms underlying language perception

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Zusammenfassung

Das Sprachverstehen erfordert ein komplexes Zusammenspiel verschiedener mentaler Prozesse. Zuerst muss der kontinuierliche akustische Sprachstrom in einzelne Einheiten wie z.B. Wörter und Phrasen unterteilt werden. Im Sprachstrom enthaltene segmentale und suprasegmentale Informationen unterstützen diesen Segmentierungsprozess und ermöglichen das Sprachverstehen. Wissen über die zugrunde liegenden neuronalen Mechanismen dieser Prozesse ist wesentlich für das allgemeine Verständnis der Sprachverarbeitung und insbesondere der Sprachentwicklung, bei der die Segmentierung des akustischen Sprachstroms eine wichtige Rolle spielt. Bei Erwachsenen scheinen fronto-temporale Regionen der linken bzw. rechten Hirnhälfte für die Verarbeitung segmentaler bzw. suprasegmentaler Information spezialisiert zu sein. Umfassende Ergebnisse zu neuronalen Mechanismen der Sprachentwicklung fehlen bislang. Die vorliegende Dissertation untersucht neuronale Korrelate der Verarbeitung sprachrelevanter akustischer Information bei Erwachsenen und Kleinkindern mittels kombinierter Nahinfrarot-Spektroskopie- und Elektroenzephalographie-Messungen. Studie I untersucht die zeitlichen und topographischen Verarbeitungsprozesse phonotaktischer Information bei Erwachsenen und bildet damit eine wesentliche Grundlage für die Interpretation zukünftiger Untersuchungen dieser Prozesse bei Kleinkindern. Phonotaktik, die möglichen Kombinationen der Phoneme einer bestimmten Sprache, dient als wesentlicher Hinweisreiz bei der Segmentierung des Sprachstroms. In Übereinstimmung mit den Annahmen des „Dynamic Dual Pathway“ Modells führt segmentale phonotaktische Information zur Aktivierung eines links-hemisphärischen Netzwerkes. Ob diese Lateralisierung auf die linguistischen oder auf die akustischen Eigenschaften der Stimuli zurückzuführen ist bleibt unklar. Befunde aus Erwachsenen-Studien weisen darauf hin, dass die lateralisierte Verarbeitung linguistischer Funktionen aus der Spezialisierung des auditorischen Kortex für bestimmte zeitliche akustische Modulationen im Sprachsignal resultiert. Ob sich diese Asymmetrie bereits in der frühen Kindheit finden lässt, untersuchen Studie II und III. In diesen Studien werden nichtsprachliche akustische Reize verwendet, deren zeitliche Struktur so variierte, dass sie den im Sprachsignal vorhandenen zeitlichen Frequenzmustern entspricht. Studie II zeigt, dass bereits bei Neugeborenen diese zeitlichen Modulationen zu differenzierten und lateralisierten Verarbeitungsmustern führen. Diese Verarbeitungsmuster scheinen über die ersten Lebensmonate zu einem großen Teil konstant zu bleiben (Studie III). Die Ergebnisse unterstützen die Annahme, dass die lateralisierte Verarbeitung von Sprachreizen auf eine Spezialisierung des auditorischen Kortex für bestimmte zeitliche Frequenzmuster zurückzuführen ist. Akustische Verarbeitungsprozesse scheinen eine wesentliche Rolle bei der Sprachentwicklung zu spielen. Das Gehirn ist von Geburt auf die Wahrnehmung der zeitlichen akustischen Variationen spezialisiert, die für die Entschlüsselung des Sprachsignals relevant sind.

Schlagwörter:

Sprachentwicklung, Auditorische Verarbeitung, Neugeborene ,Säuglinge, Elektroenzephalography, Nahinfrarot-Spektroskopie

Abstract

The comprehension of spoken language requires a complex interplay of mental subprocesses in time. First of all, the continuous acoustic speech stream needs to be segmented into smaller units, such as words and phrases. Segmental and suprasegmental linguistic information are auditory cues that guide the segmentation process thus aiding language comprehension. Getting better insights into the underlying neuronal mechanisms is crucial for understanding the general nature of language perception, and language acquisition for which segmenting the acoustic stream is an important prerequisite. In adults, a number of studies provided evidence for the functional specialization of fronto-temporal regions in the left and right hemisphere for processing segmental and suprasegmental cues. Despite its relevance experimental evidence concerning the development of neuronal correlates underlying speech perception in infancy is still sparse.

The present dissertation aimed to determine neuronal mechanisms underlying the perception of basic auditory cues relevant for the segmentation of the continuous speech signal in adults and infants by applying concurrent recordings of near-infrared spectroscopy and electroencephalography.

Study I assessed the temporal and topographic characteristics of phonotactic processing in adults, thus, forming the basis for the interpretation of future studies on phonotactic processing in infants. Phonotactics describes the possible order of phonemes in a given language. Phonotactic rules are important segmental cues that aid the segmentation process. The results support the assumptions of the dynamic dual pathway model by demonstrating that segmental aspects including phonotactics recruit a specialized left hemispheric network. Whether these asymmetries can be considered a function of linguistic attributes or a consequence of basic temporal signal properties is under debate. Several studies in adults link hemispheric specialization for certain aspects of speech perception to an asymmetry in cortical tuning and reveal that the auditory cortices are differentially sensitive to temporal features of speech. Whether this asymmetry is already established in infancy is addressed by study II and III. These studies used acoustic non-linguistic sounds that vary in their temporal structure, thus sharing critical temporal acoustic features with language. Study II reveals that newborns process these temporally varying stimuli in a differential and lateralized fashion. Study III indicates that this lateralization pattern remains relatively constant over the first months of life. These findings support the notion that a more general specialization for different acoustic properties can be considered the basis for the observed lateralization of language functions. The data provide further evidence that language acquisition is linked to basic capacities in auditory processing, and reveal that from birth the brain is tuned to critical temporal properties of linguistic signals.

Keywords:

Language acquisition, Auditory processing, Newborns, Infants, Electroencephalography, Near-infrared Spectroscopy

Table of contents

1 List of original publications

This dissertation is based on the following original research publications:

Study I

Rossi, S., Jürgenson, I.B., Hanulíková, A., **Telkemeyer, S**., Wartenburger, I., Obrig, H. Implicit Processing of Phonotactic Cues: Evidence from Electrophysiological and Vascular Responses. (2010). Journal of Cognitive Neuroscience. Epub ahead of print.

Study II

Telkemeyer, S., Rossi, S., Koch, S.P., Nierhaus, T., Steinbrink, J., Poeppel, D., Obrig, H., Wartenburger, I. Sensitivity of newborn auditory cortex to the temporal structure of sounds. (2009). Journal of Neuroscience. 29(47):14726 –14733.

Study III

Telkemeyer, S., Rossi, S., Nierhaus, T., Steinbrink, J., Obrig, H., Wartenburger, I. Acoustic processing of temporally modulated sounds in infants: evidence from a combined near-infrared spectroscopy and EEG study. *Submitted.* Frontiers in Language Sciences.

2 Theoretical background

2.1 Introduction

Communication is one of the major human needs and each of us is using language every day to communicate with others. Besides the production of language, communication also includes the comprehension of what other people are saying. The comprehension of spoken language is a rather complex mental process that requires the coordination of a number of subprocesses in time. Nevertheless, our brain manages these comprehension processes with ease. If we listen to an unknown language we certainly notice how difficult it is to even identify smaller units, like words, within the speech stream. Because the brain is excellently trained in decoding the speech stream of our native language, we do not realize the effort that is necessary to extract the segmental information from the speech stream, that is, the identification of phonemes, words, and syntactic elements, and the comparison of this information to that stored in our lexicon to finally understand the meaning. To fully comprehend what a person is saying, it is also necessary to decode the suprasegmental information from the speech stream, that is, the prosody signaling the separation of different constituents and the stress pattern of relevant words in the speech stream. Thus, prosody refers to the rhythmic and melodic properties of language. Segmental and suprasegmental information are relevant cues that help the listener segmenting the speech stream thereby supporting language comprehension (Friederici and Alter, 2004). One of the segmental cues that listeners rely on during spoken word recognition is phonotactics. Phonotactics defines possible combinations of phonemes in a given language. Phonemes are the contrasting element in word pairs that signal a difference in meaning (e.g., broom – groom). Thus, phonotactics aid rapid and efficient language comprehension because they guide the detection of word boundaries, syllables and morphemes. While segmental information such as phonotactics varies within tens of milliseconds, suprasegmental information such as prosody usually spans across several phonemes, segments, phrases or sentences, hence varies more slowly. Prosodic cues help the listener to extract linguistic information such as the sentence modus (i.e., statement, question, request), the information structure (e.g., accentuation of important information in a sentence), or the syntactic structure.

While these acoustic cues are used by the adult listener to finally extract the meaning of the speech stream, they play a particular role during language acquisition in infancy. Mehler et al. (2004) suggest that infants first extract the acoustic and phonological properties and use those to extract syntactic rules. One possible source of information that infants might use to segment the speech stream is the previously described phonotactics. Some types of phonotactic sequences (e.g., [tl], [mr]) never occur at the beginning of a German word. So when listeners encounter these in fluent speech, they cannot rely on them to clearly indentify the onset of a new word. A number of studies have shown that phonotactic cues are used by the infant to segment words from the speech stream (e.g., Jusczyk et al., 1999; Friedrich and Friederici, 2005; Gervain and Mehler, 2010). In language acquisition, not only knowledge of the segmental but also of the suprasegmental organization of native language utterances appears to play a critical role. The infant is able to use prosodic boundaries, marked by vowel lengthening, pitch change and pause, to divide longer utterances like phrases or sentences into smaller linguistic units (Gleitman and Wanner, 1982; Männel and Friederici, 2009). Together the ability to segment words plus the ability to divide utterances into coherent chunks may allow the infant to learn about the distribution properties of certain elements that recur frequently in speech. Hence, the segmentation of the incoming acoustic speech stream into smaller units is an important prerequisite for language comprehension in adults but also during language acquisition in infancy.

2.2 Neuronal correlates of language perception in adults

The investigation of how the adult brain solves the complex task of language perception has been the focus of a large number of studies using different methodological approaches. The post mortem investigation of patients suffering from aphasia over a century ago provided first evidence for a hemispheric asymmetry of specific language functions (Broca, 1861; Wernicke, 1874). The development of non-invasive methods, like functional magnetic resonance imaging (fMRI) or electroencephalography (EEG) during the last decades has made it possible to get more detailed insights into the functional organization of the brain including language processing, specifically regarding the lateralization of language functions (for reviews, see Friederici, 2002; Zatorre et al., 2002; Tervaniemi and Hugdahl, 2003). Figure 1 gives an overview about those brain regions involved in the perception of language.

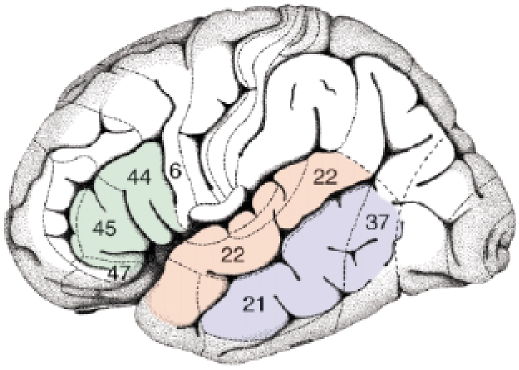

Figure 1 (from Friederici, 2002): Areas of the brain important for language perception. Brodmann areas (BA) in the left hemisphere. The inferior frontal gyrus (IFG) is shown in green, the superior temporal gyrus (STG) in red, and the middle temporal gyrus (MTG) in blue. BA 44 and 45 are traditionally defined as Broca's area.

The dynamic dual pathway model of language comprehension (Friederici and Alter, 2004) integrates observations regarding the operation of left hemispheric activations during the perception of segmental information (Hickok and Poeppel, 2000) as well as the involvement of the right hemisphere during the perception of suprasegmental information (Zatorre et al., 2002; Meyer et al., 2002). The model proposes that left and right hemispheric pathways interact dynamically during the processing of language. The first pathway devoted to the processing of segmental information is located in the left hemisphere. This pathway comprises distinct neuronal circuits. For relating word input to meaning stored in the lexicon the left temporo-parieto-occipital junction is recruited (Hickok and Poeppel, 2000). The perception of syntax and semantic is assumed to be associated with two distinct circuits in left fronto-temporal regions (Friederici, 2002). The second pathway located in the right hemisphere, specifically in right temporo-frontal regions (Meyer et al., 2002), is devoted to suprasegmental information processing. The dynamic dual pathway model incorporates the dynamic interaction between syntactic and prosodic information mediated by the corpus callosum (Friederici et al., 2007). It assumes that the respective pathways are activated by particular features of the speech stimuli. For example, syntax and semantics are thought to predominantly recruit the left hemisphere, while prosody is processed in the right hemisphere. If the stimulus' content becomes more linguistic, for example, comprising lexico-semantic information like in tonal languages such as Mandarin Chinese, the left hemisphere becomes more engaged in processing the prosodic information (Gandour et al., 2004; Tong et al., 2005).

Notably, the described language networks do not seem to be domain specific, since, for example, the processing of music recruits similar brain networks as the processing of prosody, and elicits a stronger response in the right hemispheric pathway (Tervaniemi et al., 2000; Koelsch et al., 2002; Zatorre, 2003). Thus, it has been argued that not the linguistic properties itself but the basic acoustic properties of the auditory stimuli might drive the observed hemispheric specialization. The auditory cortices might be specialized for temporal resolution, that is, the decoding of rapid changes within the acoustic signal, and for spectral resolution, for example, the perception of pitch variations. Zatorre and Belin (2001) presented either spectrally compared to temporally varying tone stimuli to adult subjects in a positron emission tomography (PET) study. They demonstrated that temporal and spectral information activate bilateral areas in the auditory cortex, however, the response to temporal features was stronger in the left hemisphere, while spectral variations elicited a stronger right hemispheric activation. The authors conclude that the left hemispheric auditory cortex is specialized for processing rapid auditory information, as it is present in the speech signal, while the right auditory cortex is specifically tuned for the processing of spectral information, as present in sentence-level prosody or music.

A similar approach linking hemispheric specialization for certain aspects of speech to asymmetries in cortical tuning was established by Poeppel (2003), and Hickok and Poeppel (2007). The multi-time resolution model postulates that speech is concurrently processed on two timescales by two separate streams. Thus, the information within the acoustic speech stream is extracted in two temporal integration windows. Extraction of segmental information (such as, determining the phonotactic difference between 'pets' and 'pest'), requires decoding of rapidly varying acoustic information in temporal windows ranging from ~20-50 ms. Suprasegmental information, commensurating with the acoustic enevelope of spoken utterances such as prosody, occurs over longer intervals, roughly around 150-300 ms. The revised version of this multi-time resolution model (Hickok and Poeppel, 2007; Poeppel et al., 2008) assumes that fast acoustic variations are symmetrically processed in left and right auditory cortices, while slow acoustic variations lead to a hemispheric lateralization favouring the right side. Functional MRI data support the hypotheses of the multi-time resolution model. Boemio et al. (2005) presented noise sounds to adult listeners that were modulated at different temporal rates within the predicted windows relevant for the decoding of segmental and suprasegmental information. They demonstrated that right compared to left superior temporal cortex shows greater blood-oxygen-level-dependent (BOLD) signal changes in response to slow (150-300 ms) acoustic modulations (see also, Overath et al., 2008; Warrier et al., 2009). Rapid temporal transitions (12-50 ms), however, were processed bilaterally, thus leading to symmetrical activation of left and right auditory cortices. These findings and the previously stated assumption of the multi-time resolution model suggest that the traditional view of the left hemisphere being uniquely specialized for processing segmental (i.e., fast temporal) information needs to be revised. Instead, a hierarchical organization of the pathways devoted to language perception has been suggested (Binder et al., 2000; Scott et al., 2000; Poeppel, 2003; Liebenthal et al., 2005). Based on experimental evidence, it has been hypothesized that along this pathway the early auditory analysis of the speech signal is mediated bilaterally in the auditory cortices, while later stages such as the processing of semantic information involve cortical subsystems that predominantly engage the left hemisphere (Binder et al., 2000; Hickok and Poeppel, 2000; Poeppel et al., 2004; Liebenthal et al., 2005).

2.3 Neuronal correlates of language acquisition during the first months of life

In the previous chapter the complexity of the mental processes underlying speech perception in adults has been emphasized. Although facing the same problem of being confronted with a complex auditory signal that they need to decode, infants learn language rapidly and effortlessly. Already during the first year of life, the infant is passing important milestones of the language acquisition process regardless of culture (for an overview, see Figure 2).

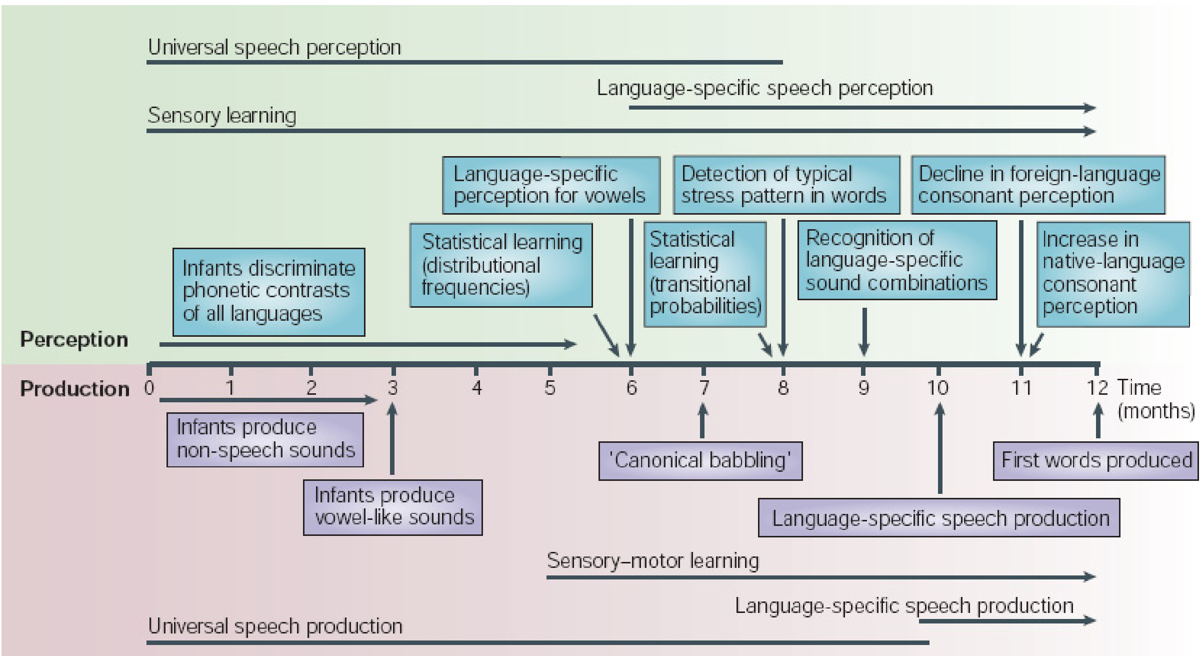

Figure 2 (from Kuhl, 2004): The universal timeline of changes in speech-perception and speech-production during the first year of life.

Long before the infant's first utterances, receptive language skills have developed. Generally, the infant seems to be tuned to perceive language. Behavioral studies showed that from birth, speech compared to acoustically matched nonspeech sounds is strongly preferred in normally developing children (Vouloumanos and Werker, 2004; Vouloumanos and Werker, 2007). Besides this major "interest" in language per se, the newborn seems to be equipped with perceptual abilities to detect acoustic differences within the speech stream. Newborns prefer their mothers voice over other female voices (Mehler et al., 1978), and detect acoustic cues that signal word boundaries (Christophe et al., 1994). They can distinguish their native language from other rhythmically different languages (Mehler et al., 1988) even if they have never heard any of the languages before (Nazzi et al., 1998). The ability to perceive and discriminate acoustic features from the auditory speech stream is an important prerequisite for language acquisition in infancy, because it forms the basis for segmentation of the speech stream into smaller linguistic units such as words (Mehler et al., 2004; Gervain and Mehler, 2010). In particular, one of the skills critical for decoding the speech stream is the ability to perceive and categorize auditory signals occuring within tens of milliseconds (Aslin, 1989; Benasich et al., 2006). As a clinical example, it has been reported that infants with a deficit in differentiating rapidly varying auditory stimuli are more likely to develop a specific language impairment (Benasich and Tallal, 2002; Choudhury et al., 2007).

But how does the infant's brain tackle the challenging problem of selecting linguistically relevant cues from a complex continuous auditory input? Since non-invasive neuroimaging methods such as EEG or near-infrared spectroscopy (NIRS) have been proven feasible for research with infants and children (for review, see Kuhl and Rivera-Gaxiola, 2008) studies on the infant brain have been dedicated to disentangle the above sketched developmental steps and discriminative abilities even before the child is able to speak and show overt responses. These studies are providing important glimpses of the mechanisms underlying the development of the human capacity for language. In particular, studies applying EEG in infants provide an important source of information for the understanding of the temporal mechanisms underlying language perception (for reviews, see Friederici, 2005; Kuhl and Rivera-Gaxiola, 2008; Gervain and Mehler, 2010). For example, Molfese and Molfese (1985; 1997) suggest that the auditory evoked potentials (AEPs) reflect mechanisms underlying the fine-grained auditory analysis necessary for the perception of phonemic boundaries. In a longitudinal design the authors demonstrated that newborns with low language skills at the ages 3 and 5 years exhibited a different morphology of the AEPs for consonant discrimination compared to newborns showing good language performances later in life. In line with the above reported findings, these EEG results further highlight that language acquisition critically depends on basic auditory perception skills.

However, in general the morphology of the AEPs changes over development (Ceponiene et al., 2002; Kushnerenko et al., 2002). Studies associating particular components of the infant's AEPs with specific language functions are still sparse (Lippé et al., 2009; Picton and Taylor, 2007). Thus, future studies are needed to link the waveforms of the infant's AEPs to specific language functions and monitor them over development.

Another particular question concerns the functional organization of the developing brain for language processing. Do we find similar functional activation patterns in response to language functions in newborns, infants, and adults? A pioneering study by Dehaene-Lambertz et al. (2002) used fMRI to measure brain activity evoked by normal speech and speech played backwards in 3 month old infants. They found hemispheric asymmetries favouring the left hemisphere in response to normal speech. Another investigation using the same stimuli applied NIRS and found greater left-hemispheric activation for normal speech already in newborns (Pena et al., 2003). This left hemispheric specialization during language processing in infants has been confirmed by a number of studies (Bortfeld et al., 2007; Bortfeld et al., 2009; Minagawa-Kawai et al., 2009). Homae et al. (2006) reported also a specialization of right hemispheric cortical regions for the analysis of prosodic features to be present in 3 months old infants. A right hemispheric dominance for processing prosody has also been reported by a NIRS study in 4 year old children (Wartenburger et al., 2007). These findings in infants and children are in line with the assumptions of the previously described dynamic dual pathway model in adults (Friederici and Alter, 2004), and indicate that hemispheric specialization already appears in early infancy. The results suggest that the lateralization patterns found in infants are comparable to the findings in adults. This organization appears to be at least partly under genetic control and develops even without experience with language (e.g., in congenitally deaf individuals, Dehaene-Lambertz et al., 2008). Similar to findings in adults, a recent fMRI study in healthy newborns revealed right lateralized activation during the presentation of music excerpts, while altered (dissonant) but still musical stimuli elicited a stronger left hemispheric activation in temporal brain regions (Perani et al., 2010). Thus, the functional asymmetries of language processing during infancy might also be attributed to the hemispheric specialization of auditory cortex regions for processing spectrotemporal information. The question remains if basic acoustic properties drive this functional specialization, specifically for the observed findings in prelinguistic infants.

3 Research questions

- Which cerebral correlates support the perception of phonotactic segmental information in adults?
- Do specific acoustic features 'guide' the lateralization of the language network in prelinguistic infants?
- Is the brain endowed with functionally specialized cortical regions for the processing of linguistically relevant acoustic sounds from birth?
- Do neuronal mechanisms underlying specific language functions change over development during the first month of life?

4 Methodological background

4.1 Electroencephalography

EEG can be considered a direct measure of brain activity because it records electrical signals generated by the brain. The EEG signal is measured as voltage differences between electrodes positioned on the skull (Berger, 1929). The rhythmic, ongoing EEG reflects the summation of post-synaptic potentials of cortical pyramidal cell populations that have the same spatial orientation and are synchronously activated (for review, see Barlow, 1993). Only currents from brain sources located within a radial orientation to the skull can be measured by the EEG. Because the strength of the electric fields falls off with increasing distance, deep sources contribute less to the EEG signal compared to sources near the skull. It is therefore important to note that the activity recorded at each location cannot necessarily be attributed to neuronal activity near that region. Compensating the relatively low spatial resolution, the EEG provides an exquisite temporal resolution. Therefore, it is a suitable method to examine neuronal correlates of temporal aspects of neuronal activity correlated with simultaneous cognitive processes, for example, the perception of speech. The EEG signal can be recorded relatively easily using customized electrode caps while the participant is engaged in a cognitive task or listening to speech sounds. Because the method allows to record brain activity in a relatively natural setting, it is widely used to monitor brain development by measuring newborns, infants, and children (Picton and Taylor, 2007). The EEG is specifically suitable to test hypotheses concerning language development in prelinguistic infants because it provides reliable information about disciminative abilities and hypotheses that predict a temporal succession of steps affording linguistic operations (Friederici, 2005). One possible way to analyse the EEG signal in response to cognitive tasks is the extraction of event-related potentials (ERPs) from the ongoing EEG. The EEG waveform reflects neuronal activity from all parts of the brain. Some of the activity may be specifically related to the current task but most of it is related to spontaneous activity of other neurons that do not directly contribute to the task. Through averaging the EEG signal over many stimulus presentations relative to stimulus-onset the signal-to-noise ratio can be increased. The resulting ERP waveform for each electrode and each stimulus condition possesses either negative or positive polarities. In the last decades of ERP research characteristic components in response to specific stimuli have been described. Acoustic stimuli, for example, elicit a characteristic ERP, the so called AEP that consists of the typical P1-N1-P2 waveform in adults (Näätänen and Picton, 1987). The abbreviations describe the polarity and the sequence of the component, thus, P1 describes the first Positivity, N1 the first Negativity, and P2 the second Positivity (see, Figure 3).

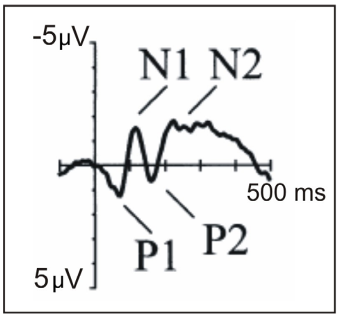

Figure 3 (from Ceponiene et al., 2002): Morphology of the adult's AEP, recorded at the Fz electrode.

In adults, the AEP is associated with sound detection and is modulated by temporal, physical and attentional aspects related to the auditory stimulus information (Näätänen and Picton, 1987). In newborns and infants the AEP can also be elicited but exhibits differences in morphology and also scalp distribution (Kushnerenko et al., 2002; Picton and Taylor, 2007). Therefore, monitoring the development of the AEP can provide information about the development of the underlying brain regions engaged in the perception of auditory information like speech. Another example for a characteristic component reflecting specific language processes is the N400, a negativity peaking around 400 ms after stimulus onset. This component is assumed to reflect the process of searching for lexico-semantic categorization, that means, it indicates the access of stored information in the lexicon (Kutas and Federmeier, 2000; Lau et al., 2008). The N400 component is also used to monitor language acquisition processes, for example, it differentiates between infants with high and low early word production at the age of 12 months (Friedrich and Friederici, 2010).

ERPs indicate maturational changes or discriminative abilities but do not capture the spectral or temporal course of the oscillatory activity of neuronal essembles (Shahin et al., 2010). Continuous EEG can be decomposed into oscillatory components by applying, for example, wavelet analyses, which allows the inspection of the EEG signal as a function of time and frequency (Tallon-Baudry and Bertrand, 1999; Jensen et al., 2002). Brain oscillatory systems have been proposed to act as neuronal communication mechanisms, thus dynamically connecting different brain regions. Neuronal oscillatory activity is caused by complex interactions between inhibitory and excitatory mechanisms, either by single neurons mediated by intrinsic membrane properties or on the level of networks mediated by local inhibitory interneurons and feedback loops (Lopes da Silva, 1991; Singer, 1993; Singer, 1999). One possibility to quantify oscillatory EEG responses is to assess the relative increase or decrease in signal power of cortical oscillations in specific frequency bands in a post-stimulus time interval compared to a pre-stimulus interval. Thereby a resulting event-related synchronization or desynchronization quantifies changes in signal power relative to the event (Pfurtscheller and Lopes da Silva, 1999). The specific frequency bands reflect different states of brain functioning and specific aspects of information processing.

4.2 Near-infrared spectroscopy

NIRS, also often referred to as optical topography (OT) is a unique tool to non-invasively assess cerebral oxygenation changes. In contrast to EEG, vascular imaging techniques such as NIRS and fMRI provide indirect measures of neuronal brain activation. They rely on the principles of the neuro-vascular coupling assuming that in an activated cortical area the increased demand in oxygen and glucose is met by a local increase in blood flow. This blood flow increase overcompensates oxygen consumption leading to a focal hyperoxygenation when compared to 'rest' (Fox and Raichle, 1986). Thus, increased blood flow leads to concentration changes of the two major dynamic chromophores, that is, an increase in oxygenated hemoglobin (oxy-Hb), and a decrease in deoxygenated hemoglobin (deoxy-Hb). Such a decrease in deoxy-Hb is the major source of the contrast change in susceptibility weighted functional BOLD MRI. In other words, BOLD-contrast increases, termed 'activation' in the fMRI literature, are seen in areas in which NIRS measures a decrease in deoxy-Hb (Kleinschmidt et al., 1996; Obrig and Villringer, 2003). Near-infrared light (650-950 nm) is able to penetrate biological tissue. Due to the different absorption spectra of oxy- (~830 nm) and deoxy-Hb (~690 nm) they can be differentiated when light attenuation is measured at the two respective wavelengths. The two wavelengths of near-infrared light are sent through light emitting probes placed on the skull. The light travels in deeper tissue layers up to 1-2 cm depths reaching the cortex, where it is absorbed by the two chromophores, oxy- and deoxy-Hb. Next to each light emitter a light detecting probe is placed, usually at a fixed distance of 2.5 or 3 cm. The amount of detected light depends mainly on the absorption and scattering of the interrogated tissue which is amongst others conditioned through the quantity of the oxy- and deoxy-Hb concentration (for review, see Obrig and Villringer, 2003). The assessment of changes in light attenuation of the two different wavelengths are transformed into concentration changes of oxy- and deoxy-Hb based on the modified Beer-Lambert approach (Cope and Delpy, 1988). While fMRI is unsurpassed in spatial resolution, it has limitations especially in monitoring language acquisition in infancy and childhood or in specific patient populations. The strong magnetic field, the constraints on movement, and the unnatural, rather disturbing scanner environment limit the investigation of infant populations for research purposes due to ethical reasons. NIRS imposes less such restrictions because it relies on a comparatively undemanding set-up which allows for measurements in newborns and infants (Minagawa-Kawai et al., 2008; Lloyd-Fox et al., 2010). Further, the method is completely silent permitting a near natural presentation of auditory stimuli by the lack of instrumental noise. In addition, the simultaneous acquisition of EEG without any interference is of specific importance, since many domains of language processing have been reliably mirrored in differential EEG components. Furthermore, concurrent recordings of EEG and NIRS lead to the combination of both methods' advantages, the high temporal resolution of the EEG and the better spatial resolution of the NIRS.

5 Empirical studies

To answer the research questions stated above, the following studies have been conducted.

5.1 Study I: Implicit processing of phonotactic cues: evidence from electrophysiological and vascular responses

Prelexical information such as stress pattern and phonotactics are relevant cues for the segmentation and comprehension of language (for review, see McQueen, 2007). Phonotocatic rules include the possible ordering of phonetic segments in a specific language. They are important cues for language comprehension. Therefore, the acquisition of phonotactic rules is crucial during language development in infancy (Friederici, 2005), and when learning a second language (Weber and Cutler, 2006). One method of choice to investigate the neuronal underpinnings of phonotactic processing is the EEG, in particular ERPs. One ERP component associated with lexico-semantic processes is the N400, a negative shift occuring around 400 ms after stimulus onset

(Kutas and Federmeier, 2000; Lau et al., 2008). An increased N400 amplitude has been found for pseudowords compared to real words (Bentin et al., 1985; Chwilla et al., 1995). Pseudowords cannot be successfully integrated into the lexicon, leading to an increased N400. Therefore the N400 is assumed to reflect the process of searching for lexico-semantic categorization rather than its success. Pseudowords consisting of illegal phonotactics, with respect to the participants' native language, compared to legal phonotactic pseudowords elicit a smaller N400, because the illegal pseudowords are classified as nonwords already at the prelexical level (Friedrich and Friederici, 2005). The result indicates how fast the brain is extracting acoustic cues, like phonotactic cues, and integrating them with the stored information.

While the temporal processing of phonotactic cues has been investigated by means of ERPs, the cerebral correlates of phonotactic processing have not been addressed so far. Study I aimed at filling this gap by presenting phonotactically legal and illegal pseudowords to adult listeners while simultaneously measuring EEG and NIRS. For the EEG, we expected to confirm the stronger N400 effect for phonotactically legal pseudowords, that had been reported previously (Friedrich and Friederici, 2005). Based on the assumptions of the dynamic dual pathway model (Friederici and Alter, 2004), we hypothesized, that the phonotactic cues are processed predominantly in left hemispheric brain regions as they represent segmental features. Since phonotactic cues trigger lexical processes, we expected a stronger left hemispheric activation for legal compared to illegal pseudowords. The adult participants passively listened to monosyllabic pseudowords. The onset of each pseudoword varied with respect to German phonotactic legality. The onsets of the illegal pseudowords were controlled for their legality in a different language, that is, Slovak.

As hypothesized, the legal compared to illegal pseudowords lead to a significantly increased N400 amplitude in centro-parietal electrodes. Our results indicate that the adult participants use prelexical, such as phonotactic, cues to segment the acoustic speech stream into single linguistic units. Legal pseudowords preferentially initiate lexical processing, even if no lexical content is given. Furthermore, our NIRS results provide first evidence with respect to the topography and lateralization of phonotactic processing. In line with the assumptions of the dynamic dual pathway model (Friederici and Alter, 2004), the phonotactic cues activated left hemispheric fronto-temporal and temporal areas. As expected, phonotactically legal pseudowords elicited a stronger hemodynamic response compared to illegal pseudowords. Our results indicate that prelexical cues trigger lexical processing irrespective of task relevance. It has been demonstrated that phonotactic rules are relevant cues helping the infant to segment the speech stream, thus, facilitating language acquisition. Knowledge about the temporal and topographic mechanisms guiding the perception of phonotactic cues play a pivotal role to further understand language acquisition processes. A subsequent study using the same experimental paradigm and procedure is aimed to determine neuronal correlates of processing phonotactic cues in early infancy (Rossi et al., in prep.).

5.2 Study II: Sensitivity of newborn auditory cortex to the temporal structure of sounds

While the previous study and also a number of other studies have investigated cortical networks underlying specific linguistic processes in adults (Friederici, 2002; Hickok and Poeppel, 2007), the emergence of this functional organization remains unclear. Investigating functional networks of speech perception in infancy might elucidate which neuronal ensembles support critical perceptual abilities gating language acquisition.

Previous functional imaging studies demonstrated that hemispheric asymmetries favouring the left side in response to speech stimuli are present already in newborns and 3 month old infants (Dehaene-Lambertz et al., 2002; Pena et al., 2003; Dehaene-Lambertz et al., 2006). Additionally, specialization of right hemispheric cortical regions for the analysis of prosodic features has been demonstrated already in 3 months old infants (Homae et al., 2006). These results indicate that hemispheric specialization for the perception of language is present even in prelinguistic infants, however, its origin remains unclear. The observed discrimination abilities between speech versus nonspeech sounds and between different rhythmic and prosodic structures might also result from differences in basic acoustic properties of the speech signal itself. Previous studies in adults link hemispheric specialization for certain aspects of speech to asymmetries in the perception of spectrotemporal features of the acoustic speech stream (Zatorre and Belin, 2001; Schönwiesner et al., 2005; Poeppel, 2003). The multi-time resolution model (Hickok and Poeppel, 2007; Poeppel et al., 2008) postulates that the auditory cortices are differentially sensitive to the temporal structure of the acoustic speech signal. The integration of rapidly varying acoustic features (20-50 ms window) fundamental for the perception of phonetic contrasts, predominantly recruits areas in the left and right auditory cortices. Modulations of the acoustic signal at slower rates (150-300 ms) are more relevant for the extraction of suprasegmental features such as the perception of prosody. These slower acoustic modulations are predominantly processed in right-hemispheric areas. The assumptions of this hypothesis have been supported by growing experimental evidence (Boemio et al., 2005; Overath et al., 2008; Warrier et al., 2009). The ability to differentiate between temporal acoustic features is thought to play a pivotal role during language acquisition. Thus, infants with a deficit in differentiating rapidly varying auditory stimuli are more likely to develop a specific language impairment (Benasich and Tallal, 2002; Choudhury et al., 2007). Despite the relevance of the acoustic feature analysis for language acquisition, knowledge of the underlying cortical mechanisms in infants is still sparse. Study II aimed at bridging the gap between the questions if hemispheric specialization for language functions is merely driven by acoustic features within the speech signal, and if this hemispheric specialization is present from birth. In line with a previous fMRI study in adults using the same stimulus material, we presented four different acoustic noise stimuli with parametrically varying temporal structure (Boemio et al., 2005) to 3-day old newborns while concurrently assessing the hemodynamic response using NIRS and the electrophysiological response by means of ERPs. The stimuli consisted of concatenating noise segments of varying lengths (i.e., 12, 25, 160, and 300 ms) forming four different stimulus conditions with varying modulation frequency pattern, each representing relevant acoustic changes of linguistic features within the speech signal. The AEPs monitor the phasic electrophysiological response within the first second of stimulus presentation. AEPs were similar for all of the four acoustic modulations. The results indicate that each acoustic stimulus condition was perceived equally during the early acoustic analysis, that is, within the first second of stimulus presentation.

The hemodynamic response, measured by means of NIRS, revealed a differential response for all four different temporal modulations. The newborns showed an increased hemodynamic response to fast acoustic modulations, especially in the range relevant for phoneme perception (25 ms modulations). Further the data suggest that an adult-like functional asymmetry is present from birth. While fast acoustic modulations are processed in bilateral auditory cortex areas, slow acoustic modulations (160 and 300 ms modulations) elicited a larger right hemispheric activation. The results provide evidence, that from birth the brain exhibits functional properties especially tuned to language. Further the data can be interpreted along psychoacoustic models proposing that a more general specialization for different acoustic properties of the incoming acoustic signals shapes the observed lateralization of specific language functions.

5.3 Study III: Acoustic processing of temporally modulated sounds in infants: evidence from a combined near-infrared spectroscopy and EEG study

The results from study II indicate that already the newborn auditory cortex is sensitive to the different temporal features of acoustic sounds, which is a relevant prerequisite for language acquisition. In particular, a right hemispheric lateralization for slow acoustic modulations has been found. The results of the reported study emphazise the role of basic acoustic features within the speech signal that might drive the hemispheric lateralization. However, while brain regions recruited for language processing in infants are similar to those observed in adults, the intensity of the observed lateralization pattern during the perception of speech increases and consolidates during development (Holland et al., 2001). The aim of study III was to track cortical processing mechanisms of the auditory temporal signal analysis during the course of development. We therefore run the same study protocol described in study II in two other age groups, that is, 3 and 6 month old infants. We again used simultaneous assessment of hemodynamic and electrophysiological brain responses to investigate brain mechanisms during the perception of temporal variations in acoustic stimuli. Besides the analysis of the hemodynamic responses focusing on the investigation of hemispheric lateralization, we applied different analyses on the elctrophysiological data to investigate brain maturation processes. The results reveal that subtle auditory differences during the processing of complex auditory stimuli elicit a differential pattern of brain activation in infants. In line with the results in newborns reported in study II (Telkemeyer et al., 2009), our NIRS results in study III support the idea that language specific hemispheric asymmetries might to some extent be driven by acoustic features of the speech signal itself. The brain responses in 6 month old infants are modulated by the temporal variation of the acoustic stimuli. Fast acoustic modulations yield increased hemodynamic responses over bilateral temporal brain regions, whereas slow acoustic modulations resulted in a greater right-lateralized response. Thus, hemispheric asymmetries for language specific acoustic modulations seem to remain constant over development. The AEPs monitoring the phasic electrophysiological response to the onset of the averaged acoustic stimuli indicated an effect of brain maturation on the morphology of the AEPs. The AEPs of 3 and 6 month old infants showed an early negative and a later positive component. While the peak latency of the negativity was similar in both age groups, the amplitude increased with age. The positivity, on the contrary, decreased in latency with age but did not change in amplitude. These results are in line with a number of previous reports on the maturation of the AEPs during the first months of life (Kushnerenko et al., 2002; Wunderlich et al., 2006; Picton and Taylor, 2007). However, similar to the results of the NIRS, no age effect was found in the differential AEP analysis of fast compared to slow acoustic modulations. Both age groups perceived the subtle acoustic differences between temporally modulated sounds already at the onset of the stimulus. The amplitude of the negativity was increased for fast compared to slowly modulated stimuli. This negativity is thought to reflect basic auditory perception mechanisms and to be modulated by the energy of the acoustic stimulus. On the contrary, the positivity was increased for slowly modulated stimuli in both age groups. This component is modulated by conciously perceived, stimulus-specific features such as the emotional content or salience of the stimulus (Ceponiene et al., 2005; Spreckelmeyer et al., 2009). Given the importance of prosodic features (characterized by slow acoustic modulations) especially during language acquisition the increased amplitude might reflect an increased attention of the infants towards the slow modulations. The time-frequency analysis of the electrophysiological data revealed in 6 but not in 3 month old infants a stronger theta-band desynchronization for slowly modulated stimuli. Whether this developmental effect might be due to an increasing fine-grained perception for complex spectrotemporal sounds in general or reflects a stimulus-specific effect such as increased familiarity or attention towards slow acoustic modualtions remains unclear. To our knowledge, so far, no study investigated slow oscillatory responses to auditory stimulation in infants. Thus, the relation between oscillatory activity and auditory stimuli in the developing brain remains highly elusive, and needs to be addressed in future studies.

6 Discussion

Although apparently simple, the comprehension of spoken language requires a complex interplay of different neuronal mechanisms. To gain knowledge about these mechanisms is crucial for understanding the general nature of speech perception but also processes of first- and second-language learning. Both, adults as well as infants, face the problem of listening to a complex auditory signal they need to decode. The adult brain is trained to segment the speech stream and it processes the different types of information within milliseconds. Unless much progress has been done, more research is needed to understand the neuronal correlates of specific language functions in adults.

The adult's proficiency in the native language can only be achieved when learning the language early in life. Although facing the "segmentation problem", that is, extracting relevant linguistic units from the continuous auditory stream (for review, see Gervain and Mehler, 2010), infants manage the acquisition of language at a remarkably fast pace. From birth, infants are equipped with perceptual abilities supporting language acquisition. Besides the infant's general preference for speech sounds, the child is able to process, discriminate, and extract relevant acoustic information from the acoustic speech stream (see, chapter 4.3). Studying language acquisition is not easily accomplished because learning already takes place before one can behaviorally measure the infant's language perception abilities. Non-invasive neuroimaging methods such as EEG and NIRS allow to monitor neuronal mechanisms underlying language development from birth.

The present dissertation aimed to determine neuronal mechanisms underlying the perception of basic auditory cues relevant for the segmentation of the continuous speech signal in adults and infants. Methodologically all studies were built on the new approach to combine EEG and NIRS to simultaneously measure the electrophysiological response (mainly ERPs) and the hemodynamic response reflecting neuronal brain activation.

Study I investigated the neuronal correlates of processing phonotactic rules, which are relevant segmental cues for language comprehension. We measured the ERPs, in particular the N400 component, to confirm previous findings demonstrating an increased N400 amplitude during unknown (illegal, with respect to the listeners native language) compared to known (legal) phonotactics (Friedrich and Friederici, 2005). Through simultaneous assessment of the hemodynamic response by means of NIRS, we were able to add new pieces of information about the topographical characteristics of phonotactic processing. We found increased hemodynamic responses in left fronto-temporal brain regions during the perception of phonotactically legal compared to illegal pseudowords. This left hemispheric dominance of phonotactic processing can be interpreted along the assumptions of the dynamic dual pathway model (Friederici and Alter, 2004), because phonological processing represents a segmental feature of language perception. Study I was performed in adult subjects, because the perception of phonotactic cues is a relevant condition for the language comprehension process in adults. Furthermore, findings on the topography of phonotactic processing in the mature brain are still sparse. However, due to the major importance of phonotactic cues for the segmentation process during language acquisition, we additionally conducted the same study protocol in young infants. The manuscript reporting the results of the infant study is in preparation (Rossi et al., in prep.).

If the observed hemispheric lateralization for phonotactics, thus for segmental information is based on the linguistic stimulus information itself or is (at least partially) driven by basic acoustic properties, remains unsolved in study I. Hemispheric specialization for certain aspects of speech perception might rely on an asymmetry of the auditory cortices for processing temporal (Poeppel, 2003; Poeppel et al., 2008) or spectrotemporal (Zatorre and Belin, 2001) features. Phonotactic cues, such as the transition from one phoneme to another, acoustically vary within tens of milliseconds. A former version of the multi-time resolution model (Poeppel, 2003) assumed that fast acoustic variations lead to left lateralized activation patterns in auditory cortex areas, which would intuitively fit to the results reported in study I. Based on growing experimental evidence revealing symmetric activations of left and right hemispheric regions during the perception of fast acoustic modulations (Boemio et al., 2005; Luo and Poeppel, 2007) the authors revised this model (Hickok and Poeppel, 2007; Poeppel et al., 2008). Because a hierarchical organization of the pathway devoted to language perception is assumed, the early acoustic analysis of fast acoustic modulations is thought to recruit bilateral auditory cortices. Later stages of the language perception process such as the extraction of the lexical information are thought to lateralize to the left hemisphere. For example, Liebenthal et al. (2005) suggest that the processing of phonemic information might represent an intermediate stage in a functional pathway linking areas in the bilateral auditory cortex to left lateralized areas involved in higher-level linguistic processes. From a psychoacoustic point of view this might to some extent explain the hemispheric lateralization for phonotactic processing found in study I. The multi-time resolution model further assumes a right hemispheric dominance of the auditory cortex for processing slow temporal variations within the acoustic signal. The assumptions concerning the specialization of the right hemisphere are more consistent. Further research is needed to fully identify the functional pathways of language perception in the adult brain.

The aim of study II and III was to determine whether the immature brain processes non-linguistic stimuli sharing temporal features with language in a differential and lateralized fashion. Study II investigated if such a specialization can be found from birth. The results show that the newborn brain preferentially processes fast temporal modulations especially relevant for the perception of phonemes. In line with the revised multi-time resolution conceptions, fast modulations elicit strong bilateral cortical responses. The brain response to slow acoustic modulations is lateralized to the right hemisphere. Our findings support the notion of an innate neuronal specialization for basic temporal characteristics wich may be fundamental to language acquisition.

During the first 6 months of life the infant passes crucial milestones in acquiring its native language (Kuhl et al., 1992; Kuhl, 2004; Friederici, 2005). These are accompanied by changes in the underlying neuronal mechanisms (Holland et al., 2001; Kuhl and Rivera-Gaxiola, 2008). Study III investigated the development of the underlying cortical mechanisms with respect to the perception of temporally varying features. The results indicate that hemispheric asymmetries for language specific acoustic modulations seem to remain constant over the first 6 months of development. While the averaged AEPs for all stimulus conditions exhibit morphological changes over development reflecting general brain maturation of the temporal dynamics underlying acoustic processing, the differential AEPs in response to fast and slow acoustic modualtions did not reveal any age effect. Three and 6 month old infants were able to differentiate between the temporal acoustic modulations from the beginning of the stimulus. As a merely explorative attempt, we analysed the oscillatory electrophysiological response by applying time-frequency analyses. The data reveal that 6 but not 3 month old infants show a stronger theta-band desynchronization for slowly modulated stimuli. If this developmental effect can be interpreted as an increasing ability to process complex spectrotemporal sounds in general or if it reflects an increased attention for the slow acoustic modulations remains unsolved. Future studies are needed to elucidate oscillatory brain responses during auditory and language perception in early infancy.

In sum, the results of the present dissertation reveal new insights into neuronal mechanisms relevant for the perception of language. Our results in adults provide new information about the temporal and topographic characteristics of phonotactic processing thus forming the basis for the interpretation of future studies on phonotactic processing in infants. The results can be interpreted along the assumptions of the dynamic dual pathway model regarding hemispheric asymmetries for specific linguistic functions. However, those hemispheric asymmetries might also be explained by a more general specialization of auditory cortex regions for different acoustic properties. Our results in newborns and infants reveal hemispheric asymmetries for acoustic modulations relevant for the perception of language. The findings support the notion that a more general specialization for different acoustic properties can be considered the basis for the observed lateralization of language functions. Our data indicate that language acquisition is linked to basic mechanisms in auditory perception. The results reveal that from birth the brain is endowed with perceptual abilities serving the decoding of linguistic signals to facilitate one of the major needs of humans: to communicate.

7 Conclusions

The results of this dissertation contribute to the existing literature on neuronal correlates of language processing in adults, and basic auditory perception underlying language acquisition in infancy by suggesting the following conclusions:

- Phonotactic segmental cues are predominantly processed by left fronto-temporal cortex regions in the adult brain.
- Language acquisition is linked to basic capacities in auditory processing. From birth the brain is tuned to critical temporal properties of linguistic signals.
- In newborns the observed lateralization of language functions is related to a more general specialization of the auditory cortex for different temporal acoustic properties.
- This lateralization pattern remains relatively constant over the first months of life.

Together, the dissertation supports the view, that convergent evidence by complementary experiments in adults and infants, as well as the combination of multiple methods can help to elucidate the neuronal mechanisms underlying language perception and its development from birth.

Future studies in adults are needed to further investigate the functional pathways of language perception and the assumptions of psychoacoustic models in particular. Concerning language acquisition, results in adults provide an important basis for interpretations of infant studies. To further identify early precursors of language and the underlying neuronal mechanisms is of major importance because it may contribute to various fields of research such as the evolution of language or the quest to diagnose children with developmental disabilities that involve language

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich

- die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
- mich nicht bereits zu einem anderen Zeitpunkt oder an einer anderen Fakultät um einen Doktorgrad beworben habe und keinen Doktorgrad in dem Promotionsfach Psychologie besitze,
- und die zugrunde liegende Promotionsordnung vom 03.08.2006 kenne.

Berlin, 15.11.2010 Silke Telkemeyer

Appendix

- **Publikations- und Vortragsliste**

Publikations- und Vortragsliste

Veröffentlichte Artikel

Rossi, S., Jürgenson, I.B., Hanulíková, A., **Telkemeyer, S.,** Wartenburger, I., Obrig, H. Implicit Processing of Phonotactic Cues: Evidence from Electrophysiological and Vascular Responses. (2010). Journal of Cognitive Neuroscience. Epub ahead of print.

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Telkemeyer, S., Rossi, S., Nierhaus, T., Steinbrink, J., Obrig, H., Wartenburger, I. Acoustic processing of temporally modulated sounds in infants: evidence from a combined near-infrared spectroscopy and EEG study. Eingereicht. Frontiers in Language Sciences.

Rossi, S., **Telkemeyer, S**., Wartenburger, I., Obrig, H. Shedding Light on Words and Sentences: Optical Imaging in Language Research. Eingereicht. Brain and Language.

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