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Sustained Responses as Neurophysiological Parameter for the Assessment of Processing of Tonal Languages

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Sustained Field als neurophysiologischer Parameter für die Beurteilung von Prozessen in tonalen Sprachen

Das Verständnis der Sprachverarbeitung ist eines der ultimativen Ziele der Untersuchungen im Bereich Signalverarbeitung im auditorischen Kortex. Chinesische Töne sind hierfür der perfekte Untersuchungsgegenstand, da sie nicht nur kurz sind sondern auch komplexe linguistische Informationen enthalten. In tonalen Sprachen wie Mandarinchinesisch unterscheidet die Pitchkontur zwischen verschiedenen lexikalischen Bedeutungen, anders als in nicht-tonalen Sprachen wie Deutsch. Mit Hilfe der Magnetenzephalographie habe ich das Sustained Field (SF) von chinesischen und deutschen Muttersprachlern untersucht. Natürliche Sprachstimuli evozierten signifikant größere SF für Chinesen als für Deutsche, während ein musikalischer Ton keine signifikanten Unterschiede zwischen den Gruppen erzeugte. Das SF der chinesischen Probanden war für bedeutungstragende Stimuli größer als für bedeutungslose. Vokale, die im phonologischen System des Chinesischen vorkommen, zeigen hingegen im Vergleich zu solchen, die darin nicht vorkommen, keinen Unterschied des SF. Diese Resultate deuten darauf hin, dass das im auditorischen Kortex generierte SF einen relevanten neurophysiologischen Parameter für die Beurteilung von sprachrelevanten Prozessen darstellt.

Sustained Responses as Neurophysiological Parameter for the Assessment of Processing of Tonal Languages

To understand speech processing is one of the ultimate goals of investigations of sound processing in the auditory cortex. Chinese tones are the perfect object for this kind of investigation because they are very short but still contain complex linguistic information. In tonal languages such as Mandarin Chinese, pitch contours discriminate lexical meaning at a systematic level, which is not the case in non-tonal languages such as German. It is still unclear how such differences in phonological systems are reflected at the cortical level. Using magnetoencephalography I investigated the sustained field (SF) evoked in native Chinese and native German speakers. Natural speech stimuli evoked significantly larger SF for the Chinese than for the German group, whereas for a musical tone there was no significant difference between both group. The SF for Chinese subjects were larger when evoked by meaningful syllables as compared to meaningless ones, but there was no significant difference in the SF evoked when vowels were part of the Chinese phonological system or not. These findings suggest that the SF generated in the auditory cortex represents a relevant neurophysiological parameter for the assessment of language-related processes.

"Learning is never cumulative, it is a movement of knowing which has no beginning and no end."

(J.Krishnamurti, The Book of Life: Daily Meditations with Krishnamurti)

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1. Introduction

One of the main fields of auditory research is the investigation of sound processing in the human auditory system. Of course, one of the most important sounds for human beings is speech. It does not only contain temporal and spectral information, such as fundamental frequencies, harmonic frequencies, and frequency bands, which give hints about the sex and the size of the speaker, but also a vast of complex linguistic information that is important for our daily communication. Since speech is such an important factor in human life, a lot of research in different fields has been performed in order to achieve the ultimate goal to understand the processing of speech. There are various linguistic models, anatomical and physiological studies, studies about brain stem and cortices, which have tried to shed some light on the topic, but a lot of these processes still remain unclear.

Magnetoencephalography (MEG) and Electroencephalograhpy (EEG) are non-invasive methods to measure neural activity directly, see Sec. 2. This is done by measuring the fields or potentials outside the skull that are produced by postsynaptic currents. This dissertation deals with MEG measurements of neural responses to auditory stimuli. We are especially interested in neural responses to linguistic stimuli. For that purpose, Chinese tones are the perfect objects for this kind of investigation because they are very short but still contain complex linguistic information.

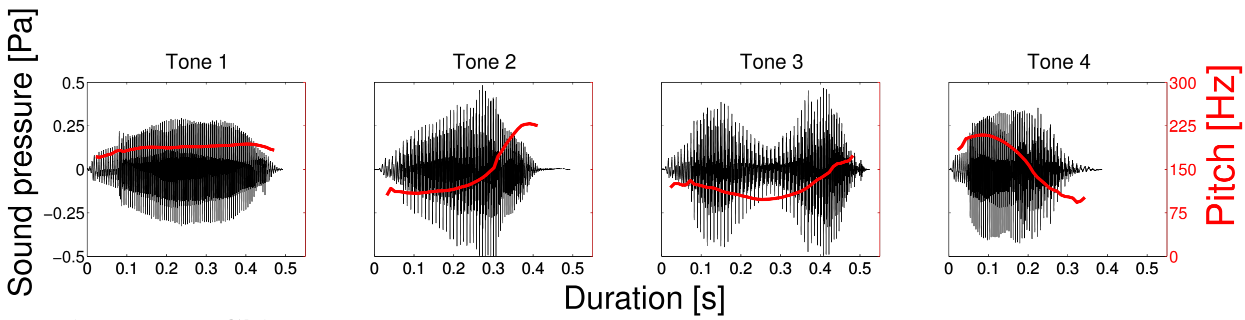


Figure 1.1: Chinese tones

In tonal languages such as Chinese pitch contours carry lexical meaning on a syllable level. By changing the pitch contour, Chinese differentiate between different words.

In this figure, the black curves show the sound pressure curves, while the red curves show the pitch contours of the four Chinese tones.

In this dissertation, I focus on Mandarin Chinese, which has four different tones as depicted in Fig. 1.1. These tones are complex sounds that have a pitch contour, which is basically the change of the main frequency f_0 over time, to discriminate meaning. Already on a syllable level, Chinese speakers distinguish between different meanings, see Sec. 2.4. We used natural speech as stimuli instead of artificial speech because we wanted to examine speech perception. Therefore, natural speech is a prerequisite.

However, pitch contours also exist in non-tonal languages, such as German, but serve a different purpose. They carry prosodic information. By changing the pitch contour, German speakers can distinguish between questions ("Er ist da?" - He is there?) and positive sentences ("Er ist da." - He is there.), see Fig. 1.2.

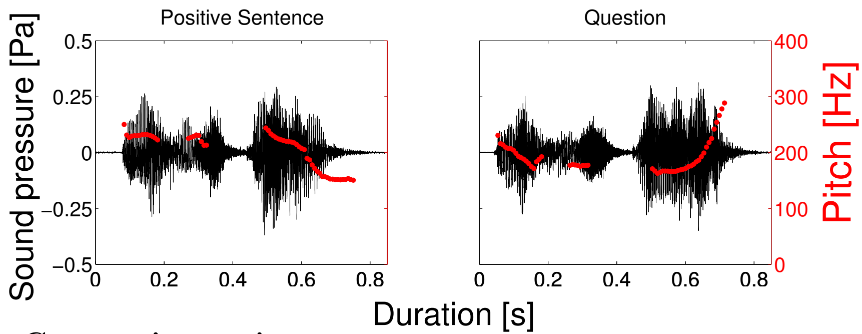


Figure 1.2: German intonation

Pitch contours in non-tonal languages carry prosodic information. By changing the pitch contour, Germans can distinguish between positive sentences ("Er ist da." - He is there.) and questions ("Er ist da?" - He is there?).

In this figure, the black curves show the sound pressure curves, while the red curves illustrate the pitch contours of German intonation.

I measured neural responses from 20 native German and 20 native Chinese speakers by recording their evoked magnetic fields with the MEG, see Sec. 3.2. The first part of the study included linguistic stimuli (vowels and syllables), while in the second part a linguistic stimulus was compared with a non-linguistic stimulus, represented by a French horn tone, see Sec. 3.1.

The data analysis was performed by using a dipole model, which simulates the measured magnetic fields with current dipoles in the brain. In Fig. 1.3 a typical example is displayed. It shows transient (P1, N1, P2) and sustained (SF) components of a typical dipole waveform.

The main result of this dissertation concerns the large language effect of the sustained field, see Sec. 4.1. The sustained field of the Chinese group is about twice the size of the German group for all linguistic stimuli, see Sec. 4.1.1. For the musical stimulus, however, we did not find any

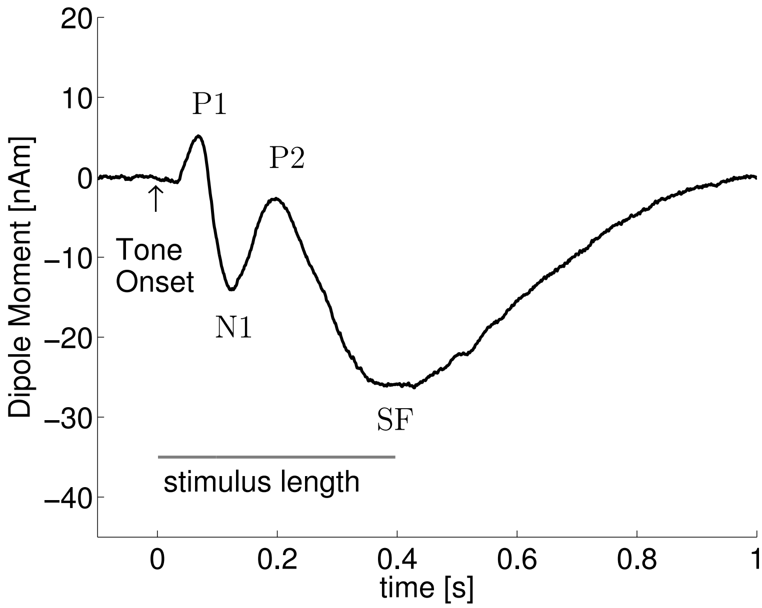


Figure 1.3: Typical dipole waveform (late latency auditory evoked potentials)

P1, the first positive peak

N1, also called N100 is the first negative peak, which occurs at around 100 ms after the onset

P2, the second positive peak, occurring at around 250 ± 50 ms

SF, sustained field, starting at approximately 300 ms; its peak is at the end of the stimulus' length.

significant differences in the sustained field between both language groups, see Sec. 4.1.2.

The results of the transient components are contrary to the sustained field, see Sec. 4.2. The N1 component does not show any differences between the groups, while the Germans' P1 and P2 components are larger than the Chinese'.

Wondering about whether the missing sustained field in some German subjects might be due to anatomical peculiarities resulting in currents that are invisible to MEG but not to EEG, a simultaneous MEG and EEG measurement for one individual subject was performed in another session, see Sec. 4.3. The subject did not show any sustained field component, neither in MEG, nor in EEG. The dipole waveforms of this subject are almost identical in both methods.

In Sec. 4.4 the results of multiple individual MEG measurements are presented to evaluate the fluctuations within an individual subject. These are indeed smaller for individuals compared to the entire group of subjects. This can also be seen in Sec. A.

The results of this dissertation are discussed in Sec. 5. Outlooks to future studies of the MEG laboratory of the Neurological Department of the University of Heidelberg are also presented.

2. Background

In this section, I will first go into detail of physics and neurophysiology of hearing (see Sec. 2.1), describing the ear and the auditory pathway. This is followed by the description of the electrostatic model of the head and neurophysical background (see Sec. 2.2), which are especially necessary for the understanding of MEG and EEG (see Sec. 2.3). At last, since neural responses of linguistic stimuli are investigated, important characteristics of linguistic background are presented. Besides, recent research results are also summarized in Sec. 2.4.

2.1. Physics and Neurophysiology of Hearing

Since the ear is the interface between the physical stimulus (sound) and the neurophysiological process, I start with the description of the ear. After following the sound through the ear to the neurons touching the hair cells, we will follow the auditory pathway from the auditory nerve to the auditory cortex.

2.1.1. The Ear

The ear is divided into three parts: the outer, middle and inner ear, see Fig. 2.1.

Because of the form of the outer ear, it is possible to collect sound waves and transmit them through the outer ear canal to the ear drum. The outer ear canal protects the ear drum and middle ear and enables the inner ear to be positioned very close to the brain, which allows short length of nerves and short travel time for action potentials. It has a length of $l \approx 2.5\,\mathrm{cm}$. Seeing it as a pipe with one open and one almost closed end, it has a resonance for $l = \frac{\lambda}{4}$, thus the standing wave frequency is $\nu = \frac{c}{\lambda} = \frac{c}{4 \cdot l} = 4\,\mathrm{kHz}$, which is the reason for high sensitivity of humans in this frequency region.

The middle ear, see Fig. 2.2, transforms air motion, which is characterized by small force and large displacement, into fluid motion of traveling waves, characterized by large forces and small displacements. It consists of ear drum, hammer (malleus), anvil (incus) and stirrup (stapes).

The oval window is the entrance to the inner ear, see Fig. 2.3. The inner ear consists of the cochlea, it is like a long tube, shaped as a spiral shell, making 2.5 turns. No other functional significance but space-saving is known to its shape. It consists of three channels (scalae), filled

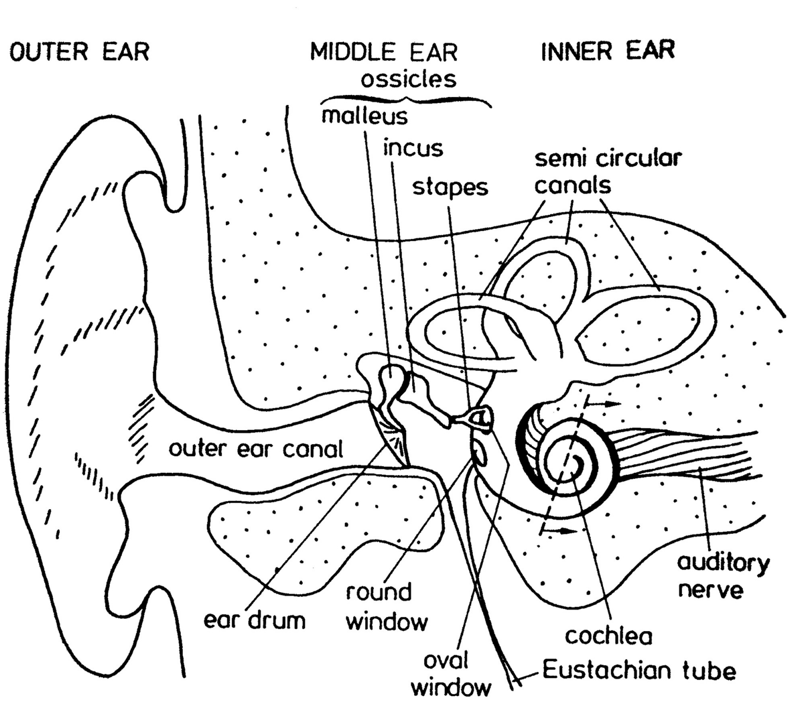


Figure 2.1: The ear

The ear is divided into three parts: the outer, middle and inner ear. The outer ear collects sound waves and transmits them through the outer ear canal to the ear drum. The outer ear canal protects the ear drum and thus the middle ear (Fastl and Zwicker, 2006, p.24). The details of the other parts of the ear are described in the following figures and also within the text.

with two different fluids. The scala vestibuli and the scala tympani are filled with perilymph, which contains high amounts of sodium (Na) resembling other body fluids, while the scala media is filled with edolymph, containing high amounts of potassium (K). Reissner's membrane divides the scala vestibuli and the scala media, while the basilar membrane separates the latter and the scala tympani.

The basilar membrane is approximately 32 mm long and can in first approximation be seen as a linear system. For high input levels through post mortem preparations, von Békésy confirmed the theory of Helmholtz that the basilar membrane separates frequencies by location, which is also called "location principle". Low frequencies produce oscillations near the apex, the helicotrema, while high frequencies produce those oscillations near the base, the oval window.

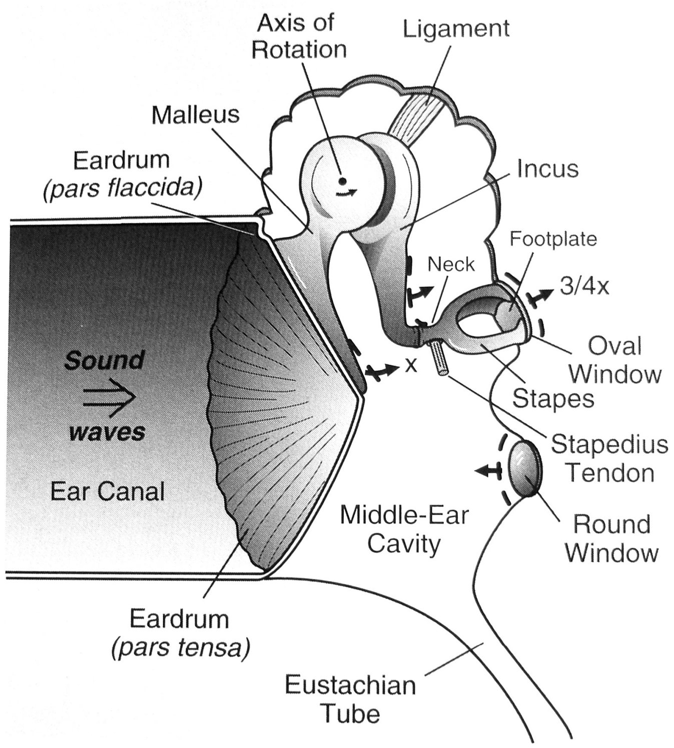


Figure 2.2: The middle ear

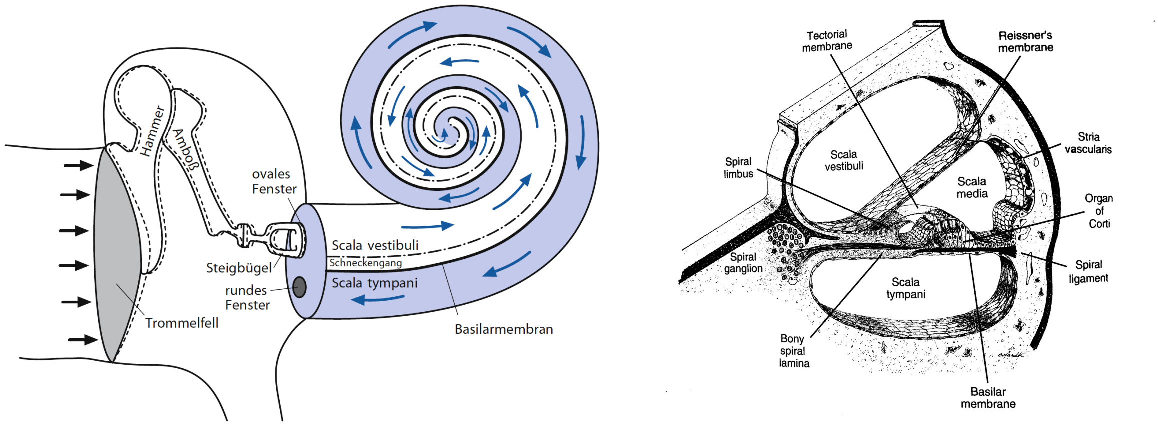
The middle ear lies between ear drum and oval window. It transforms air motion into fluid motion of traveling waves (Geisler, 1998, p.40).

Travelling waves can be seen as vertical displacement of the basilar membrane, see Fig. 2.4.

Normal, healthy ears are sharply tuned with high sensitivity to limited frequency ranges at a fixed location and require higher and higher intensities to produce responses for other frequencies.

The basilar membrane is connected to the Organ of Corti, which transforms mechanical oscillations into electrical signals, see Fig. 2.5. It contains supporting cells and sensory cells (hair cells), see Fig. 2.6. The latter can be further classified into inner and outer hair cells. There are about 12000 outer hair cells, each with 140 stereocilia, and 3500 inner hair cells, each with 40 stereocilia, which are the links to the tectorial membrane (Moore, 2003). The hair cells are connected to the fibers of the auditory nerve.

Inner hair cells are located at the inner side of the Organ of Corti in only one row. 90%



(a) Inner ear **(b)** Radial segment of cochlea

Figure 2.3: The inner ear

a) The inner ear consists of the cochlea, which is a long tube, shaped as a spiral shell to save space (Maurer et al., 2005, p.69) .

b) Here a radial segment of the cochlea is displayed. There are three channels (scalae), filled with fluids. Reissner's membrane divides the scala vestibuli and the scala media, while the basilar membrane separates the latter and the scala tympani (Geisler, 1998, p.74).

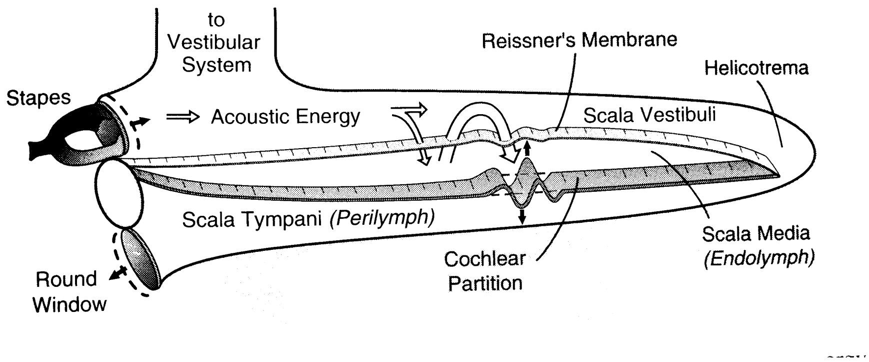


Figure 2.4: Schematic basilar membrane

The basilar membrane is approximately 32 mm long and can in first approximation be seen as a linear system. It is tonotopic. Low frequencies produce oscillations near the apex, the helicotrema, while high frequencies produce those oscillations near the base, the oval window (Geisler, 1998, p.135).

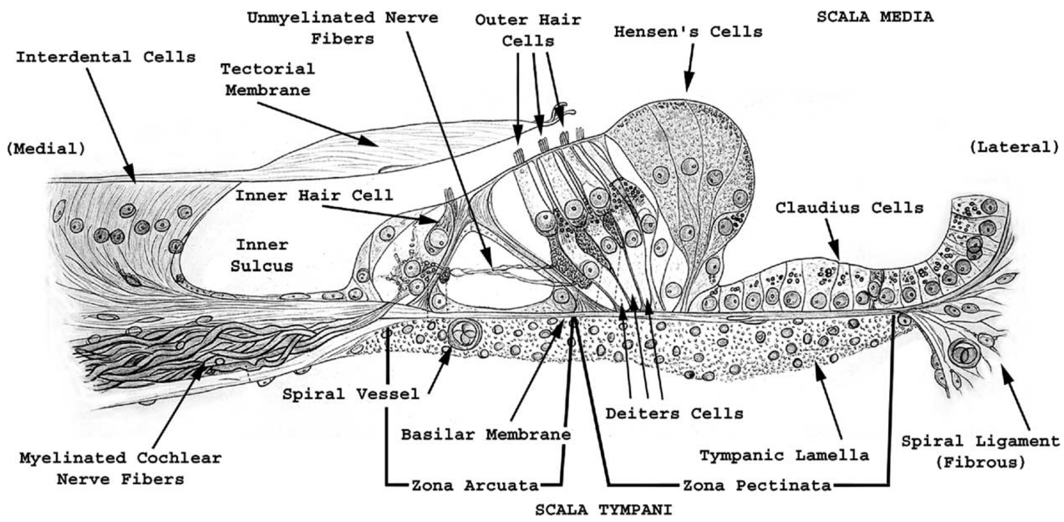


Figure 2.5: Organ of Corti

The Organ of Corti transforms mechanical oscillations into electrical signals. It contains supporting cells and sensory cells, so-called hair cells (Raphael and Altschuler, 2003, p.402).

of afferent[1] neurons make synaptic contact with inner hair cells, which accounts to about 20 afferent neurons per inner hair cell. Afferent synapses appear to possess normal characteristics of chemical synapses. The stereocilia, connected to the hair cells by “tip links”, open a flow of potassium (K) ions from the scala media, when tension is put on them by mechanical movements. This alters the voltage difference, releasing neurotransmitters and initiating action potentials in neurons of the auditory nervous system.

Outer hair cells are arranged in up to five rows in humans, they are attached to spiral limbus at the inner side of the scala media, situated at the middle of the Organ of Corti, building three rows. As can be seen in Fig. 2.6, they are pillar shaped and thinner than the inner hair cells, but not tightly surrounded by supporting cells. They are innervated very strongly by efferent[2] fibers. Their main role is to influence the cochlear mechanics by active operations, leading to high sensitivity and sharp tuning. The motor functions recline at both hair bundle at the tip and the hair cell body, reacting to electrical and chemical stimulation.

[1] *”afferent”* means transmitting information to the brain
[2] *“efferent”* means transmitting information from the brain

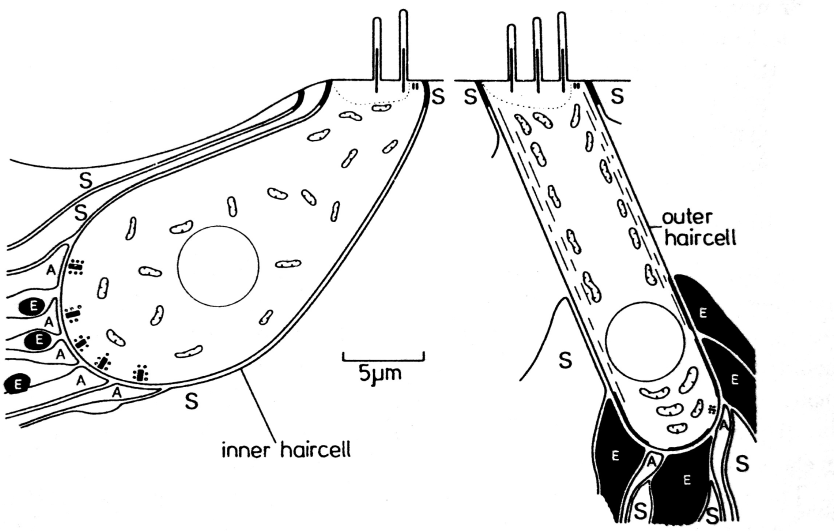


Figure 2.6: Haircells

There are about 12000 outer hair cells and 3500 inner hair cells. Inner hair cells are located at the inner side of the Organ of Corti in only one row. 90% of afferent neurons make synaptic contact with inner hair cells. Outer hair cells are arranged in up to five rows in humans, they are attached to spiral limbus at the inner side of the scala media, situated at the middle of the Organ of Corti, building three rows. They are pillar shaped and thinner than the inner hair cells but not tightly surrounded by supporting cells. They are innervated very strongly by efferent neurons. Their main role is to influence the cochlear mechanics by active operations, leading to high sensitivity and sharp tuning (Fastl and Zwicker, 2006, p.27).

2.1.2. Neurons

Neurons consist of the soma which is the cell body and mostly two kinds of extension: several dendrites and one axon, see Fig. 2.7. Dendrites receive excitement from other neurons and pass it on to the cell body, while axons transmit excitement from the cell body to the dendrites of other neurons. This location of contact is called synapse. There are 10^{11} - 10^{12} neurons inside a human's brain, with about 100,000 synapses per neuron.

The dendrites sum up the incoming signals, while the action potential is only transmitted at the axon hillock if a certain threshold is reached so that the action potential is either fully

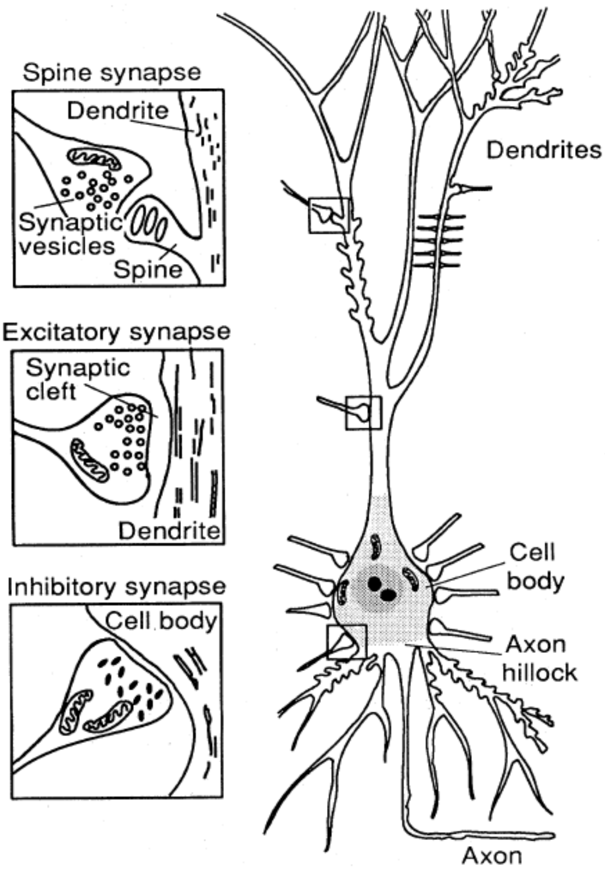


Figure 2.7: Neuron

Neurons consist of the soma which is the cell body and mostly two kinds of extension: several dendrites and one axon. Dendrites receive excitement from other neurons and pass it on to the cell body, while axons transmit excitement from the cell body to the dendrites of other neurons. This location of contact is called synapse (Hämäläinen et al., 1993, p.423).

excited or non-existent (Schmidt and Schaible, 2006, p.5ff). If it is fully excited, a neurotransmitter is released. Depending on the the sort of neurotransmitter, specific ion channels of the other neuron's membrane change their permeability to certain ions which lead to either de- or hyperpolarization. Depolarization leads to excitatory post synaptic currents and potentials, while hyperpolarization leads to inhibitory post synaptic currents and potentials. A typical post synaptic current at one synapse is approximately 20 fAm. If the same synapse is excited again within a short period of time, it leads to an even stronger depolarization which is called "temporal summation". If, however, several synapses at the same neuron are excited at the same time, the stronger depolarization is called "local summation"(Schmidt and Schaible, 2006, p.59ff).

2.1.3. The Auditory Pathway

Knowing about the auditory pathway helps to understand the neuromagnetic measurements (see Sec. 3) and results of Sec. 4.

The hair cells of the organ of Corti are connected to the auditory nerve which consists of about 30,000 neurons. 90-95% of them are efferent neurons that are bipolar, myelinated and each contact only one inner hair cell, while 5-10% are afferent neurons that are pseudounipolar, unmyelinated and each contact up to ten inner hair cells (Raphael and Altschuler, 2003).

The auditory pathway is displayed in Fig. 2.8. The part of the auditory nerve that connects to the hair cells is made of the ganglion cells of the ganglion spiral. After going through a bone lamella, the fibers unite to the N. acusticus. The auditory nerve goes along the inner auditory canal and the cerebellopontine angle until it reaches the brainstem at the dorsolateral medulla oblongata. At the nucleus cochlearis dorsalis and ventralis a shift to central neurons takes place. At the superior olive complex the change to lemniscus lateralis and its nucleus happens. The last switching station of the infratentorial area is the colliculi inferiores of the midbrain. Supratentorially, the auditory pathway goes along the corpus geniculatum mediale and the auditory cortex which lies in the Heschl's gyrus (Maurer et al., 2005).

Each auditory nerve fiber has a characteristic frequency which means it is only sensitive for a certain frequency range. Wang et al. (2005) even demonstrated that single neurons in primary auditory cortex, as well as in lateral belt areas of awake marmoset monkeys, exhibit a sustained firing pattern when driven by their preferred stimulus. In Sec. 2.4, I will go more into detail about the selective behavior of neurons of the primary auditory cortex.

In Fig. 2.9, the auditory cortex, averaged over 87 subjects, is displayed in Talairach coordinates (Schneider et al., 2005, p.1243). Talairach and Tournoux (1988) defined a standardized human brain, so that all individual brains including their anatomical structure can be normalized to this coordinate system. It is the world-wide standard for MEG, MRI, PET, etc. Schneider's map of the auditory cortex will be the reference for our later evaluation of our measurements and results, see Sec. 4. Fig. 2.9 describes where different functions are located in the auditory cortex. Tonality and melody-specific activation, for example, were found in the anterior supratemporal gyrus, while pitch-specific activation was determined in the lateral Heschl's gyrus.

In the auditory system there are four different possibilities how to code information which are probably altogether used for signal processing (Eggermont, 1998).

1. *Labeled Line Code.* A certain neuron transports one specific information. This is an important process of the tonotopic organization of the auditory path.

2. *Rate Code.* Quantitative augmentation or diminution of the firing rate codes information. This is certainly done for the sound level.

3. *Temporal Code.* Neurons fire in phase with the signal. This is probably an important code for pitch recognition and hearing of direction.

4. *Ensemble Code.* A linked ensemble of neurons transmits information. This coding is not verified but very probable.

The information of pitch is encoded twice – once using "labeled line code" and once using "temporal code". The temporal code can only be used in the very early subcortical levels of the auditory path because only then does the temporal resolution have a magnitude of ms. Later on in the cortex, the time resolution is worse than 10 ms. Therefore, the information must be altered to a pure "labeled line code" between auditory nucleus and cortex. Ruggero (1992) found evidence for labeled line code and rate code by comparing the neural tuning curves of certain neurons with the mechanical displacement of the basilar membrane.

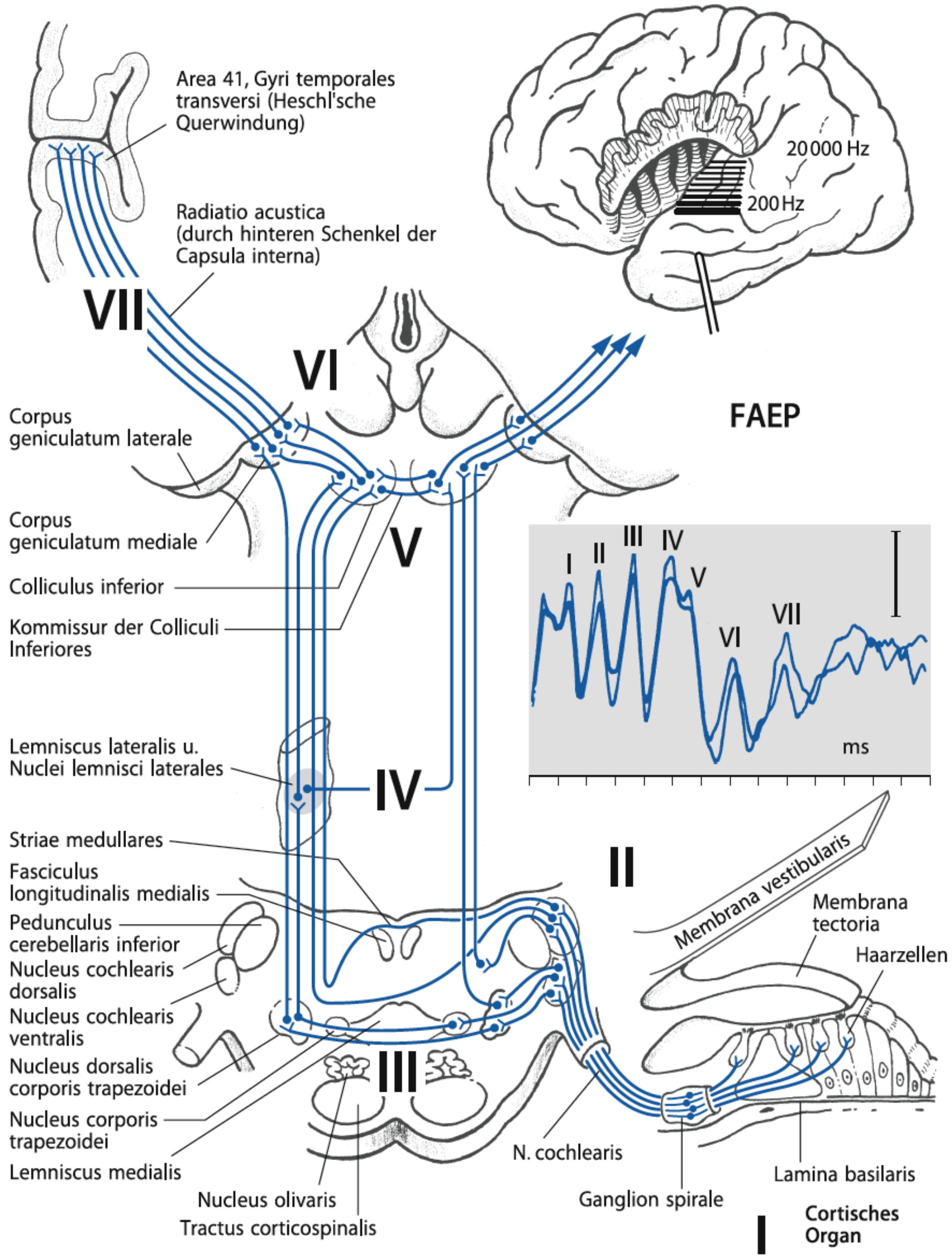


Figure 2.8: The auditory pathway

Starting at the Cortical Organ, the information travels through the auditory nerve, passing the ganglion spiral, the N. cochlearis, the inner auditory canal, the cerebellopontine angle until it reaches the brainstem. At the nucleus cochlearis dorsalis and ventralis a shift to central neurons takes place. The colliculi inferiores of the midbrain is the last switching station of the infratentorial area. Supratentorially, the auditory pathway goes along the corpus geniculatum mediale and the auditory cortex which lies in the Heschl's gyrus (Maurer et al., 2005, p.71).

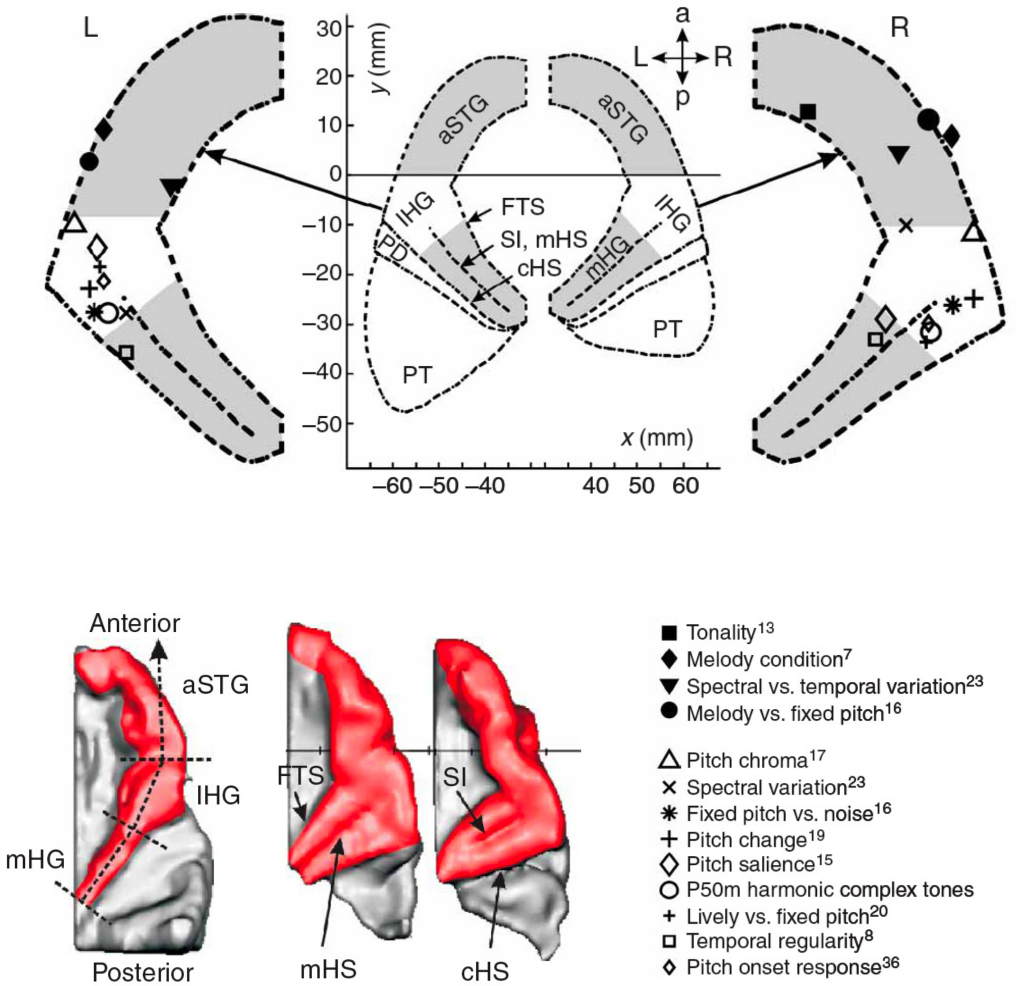


Figure 2.9: Map of the auditory cortex

In this figure a map of the auditory cortex, averaged over 87 subjects, is presented in Talairach coordinates. The map describes where different functions are located in the auditory cortex. Tonality and melody-specific activation, for example, were found in the anterior supratemporal gyrus, while pitch-specific activation was determined in the lateral Heschl's gyrus (Schneider et al., 2005, p.1243).

2.2. Head Model

Since MEG and EEG are non-invasive but direct methods to measure brain activity, the foci of our main interest are our measuring quantities: the magnetic field $\vec{B}$ outside the head and the potential ϕ on the head's surface. The magnetic field is created by the total current $\vec{j} = \vec{j_P} + \vec{j_V}$. It consists of the primary current $\vec{j_P}$, which is what we are mainly interested in – the postsynaptic current that flows within one or a few neighboring cells, and the volume current $\vec{j_V}$, which occurs over the whole brain because the primary currents create potential differences inside the brain.

A typical current dipole moment, measured with MEG, has the magnitude of several 10 fAm. With a current dipole moment of only about 20 fAm at a single synapse, as mentioned in Sec. 2.1.2, about one million active synapses are involved. This leads to a magnetic field of about 100 fT.

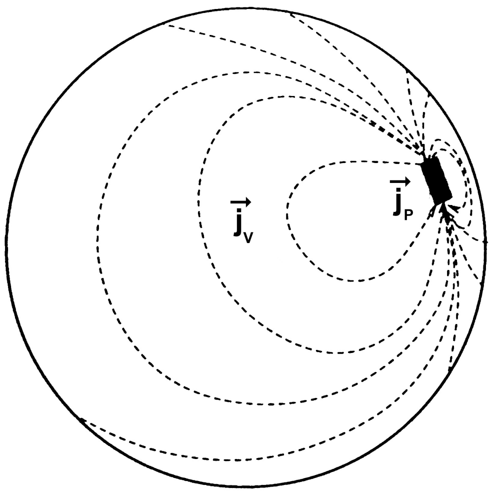


Figure 2.10: Primary and volume current

The total current is $\vec{j} = \vec{j_P} + \vec{j_V}$, consisting of the primary and the volume current. We are mainly interested in the primary current $\vec{j_P}$, which represents the postsynaptic current that flows within one or a few neighboring cells. Since the primary currents create potential differences inside the brain, the volume current $\vec{j_V}$ occurs over the whole brain as well.

Inside the head retardation effects can be neglected for frequencies relevant to neurophysics. Thus the quasi static approximation of the Maxwell equations is justified

$$\vec{\nabla} \cdot \vec{D} = 4\pi\rho \tag{1}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{2}$$

$$\vec{\nabla} \times \vec{E} = 0 \tag{3}$$

$$\vec{\nabla} \times \vec{H} = \vec{j}. \tag{4}$$

Because of Eq. 3, the electric field $\vec{E}$ can be described by the quasi static potential ϕ:

$$\vec{E}(\vec{x}) = -\vec{\nabla}\phi(\vec{x}) \tag{5}$$

Because of Eq. 2, the magnetic field $\vec{B}$ can be described by the vector potential $\vec{A}$:

$$\vec{B} = \vec{\nabla} \times \vec{A} \tag{6}$$

which fulfills the Coulomb gauge $\vec{\nabla} \cdot \vec{A} = 0$. Since inside the head $\vec{B} = \vec{H}$, Eq. 4 thus becomes

$$\vec{\nabla} \times \vec{B} = \Delta\vec{A} = \vec{j}. \tag{7}$$

From now on, G is the interior of the head and ∂G its surface.

The solution vanishes at $\vec{x} \to \infty$:

$$\vec{A} = \frac{1}{4\pi} \int_G d^3x' \frac{\vec{j}(\vec{x}')}{|\vec{x} - \vec{x}'|} \tag{8}$$

leading to

$$\vec{B}(\vec{x}) = \frac{1}{4\pi} \int_G d^3x' \frac{\vec{j}(\vec{x}') \times (\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|} = \frac{1}{4\pi} \int d^3x' \frac{\vec{\nabla}' \times \vec{j}(\vec{x}')}{|\vec{x} - \vec{x}'|}. \tag{9}$$

The total current is

$$\vec{j}(\vec{x}) = \vec{j_P}(\vec{x}) + \vec{j_V}(\vec{x}) \tag{10}$$
$$= \vec{j_P}(\vec{x}) + \sigma(\vec{x})\vec{E}(\vec{x}) \tag{11}$$
$$= \vec{j_P}(\vec{x}) - \sigma(\vec{x})\vec{\nabla}\phi(\vec{x}) \tag{12}$$
$$= \vec{j_P}(\vec{x}) + \phi(\vec{x})\vec{\nabla}\sigma(\vec{x}) \tag{13}$$

σ being the electric conductivity of the brain and ϕ the electrostatic potential, one can express the magnetic field as

$$\vec{B}(\vec{x}) = \frac{1}{4\pi}\int_G d^3x' \frac{\left(\vec{j_P}(\vec{x}') + \phi(\vec{x}')\vec{\nabla}'\sigma(\vec{x}')\right) \times (\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|}. \tag{14}$$

Because of Eq. 7: $\vec{\nabla}\cdot\vec{j} = \vec{\nabla}\cdot\left(\vec{\nabla}\times\vec{B}\right) = 0$. With the help of Eq. 13, it leads to:

$$\vec{\nabla}\cdot\vec{j_P} = -\vec{\nabla}\cdot\vec{j_V} = \vec{\nabla}\cdot\left(\sigma\vec{\nabla}\phi\right) = \sigma\Delta\phi \tag{15}$$

The conductivity depends on the position because it is zero outside the head, but non-zero inside, even when assuming homogeneous conductivity. If the head was a perfectly spherically symmetric system, $\sigma(\vec{x}) = \sigma(|\vec{x}|)$, the contribution of the volume current to the normal component of $\vec{B}$ on the head's surface would be zero

$$\hat{n}_{\partial G}\cdot\vec{\nabla}\phi = 0. \tag{16}$$

For small volume elements where $\vec{j_P} \neq 0$, it can be replaced by

$$\vec{j_P}(\vec{x}) \approx I\vec{l}\delta(\vec{x} - \vec{x_Q}) = \vec{Q}\delta(\vec{x} - \vec{x_Q}) \tag{17}$$

with $\vec{x_Q}$ is the position of the primary current density, the current strength I, the direction vector of the current density $\vec{l}$ and the current dipole $\vec{Q} = \int d^3x'\vec{j_P}(\vec{x}')$. Thus the contribution of the primary current to the magnetic field described by the current dipole $\vec{Q}$ at the position $\vec{x_Q}$ is given by:

$$\vec{B_P} = \frac{1}{4\pi}\frac{\vec{Q}\times(\vec{x} - \vec{x_Q})}{|\vec{x} - \vec{x_Q}|^3}. \tag{18}$$

$$B_n = -\hat{n}_{\partial G} \cdot \vec{\nabla}\phi(\vec{x}') \tag{19}$$

Only the primary current contributes to the normal component of the magnetic field.

2.3. MEG and EEG

Magnetoencephalography (MEG) and electroencephalography (EEG) are both direct methods to measure brain activity; the former measuring magnetic fields induced by postsynaptic currents in apical dendrites (Hansen et al., 2010), while the latter measures potentials.

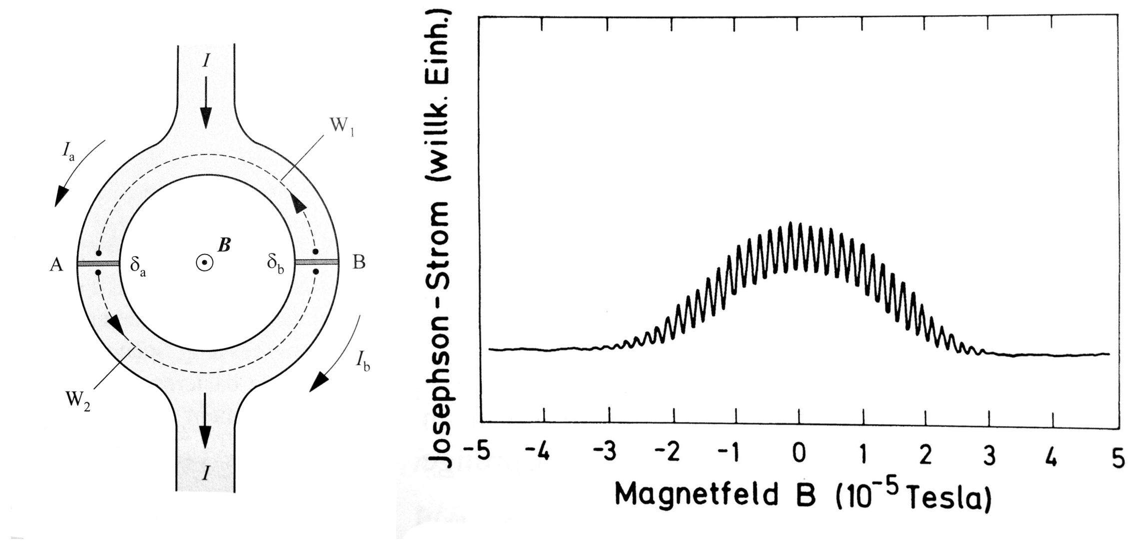
The challenge is to obtain the sources of the measured magnetic fields and potentials on the surface of the head, the so-called "inverse problem". Vice versa it is straightforward to calculate the fields and potentials from given sources. Unfortunately, von Helmholtz has already shown in 1863 that there is no unique solution to the inverse problem. This is because of the non-vanishing volume currents that do not leave any signals on the surface of the head – for example radial currents do not create any magnetic fields outside the head. Fortunately for us, the primary currents of the auditory cortex are mostly parallel to the head's surface and thus measurable using the MEG.

The advantage of MEG over EEG is the better spatial resolution that gives a reasonable dataset. Since the magnetic fields of the brain are very small, only $B_{brain} = 10 - 1000$ fT, which is $10^8 - 10^{10}$ times smaller than the earth magnetic field ($B_{earth} = 30 - 60$ µT), it is necessary to use SQUIDs (Superconducting Quantum Interference Devices) and to exploit the signal-to-noise-ratio

$$\frac{S}{N} \propto \sqrt{n} \tag{20}$$

with n being the amount of signals. By using a high number like $n = 200$ as in our case, we receive great looking, smooth curves without the need of filtering.

SQUIDs are very sensitive magnetometer, which are used to measure small changes of magnetic fields (10^{-14} T = 10 fT) and which serve as highly sensitive amperemeters and voltmeters. To ensure the operating temperature for superconductivity of the SQUIDs, helium has to be filled into the system twice a week. SQUIDs basically consist of superconducting rings or cylinders with one or two weakly coupled links operating as Josephson junctions (Hunklinger, 2007), see Fig. 2.11.



(a) Josephson junction **(b)** Josephson current

Figure 2.11: Josephson junction

SQUIDs basically consist of superconducting rings or cylinders with one or two weakly coupled links operating as Josephson junctions. The overall current I_s consists of the two currents from both junctions (Hunklinger, 2007, p.480). The current is extremely sensitive to small changes of the magnetic field.

These two parallel identical Josephson junctions (Fig. 2.11), with the magnetic field vertical to the plane of projection, are hence observed. The overall current I_s consists of the two currents from both junctions:

$$I_s = I_J\left(\sin\delta_a + \sin\delta_b\right) \tag{21}$$

$$= 2I_J \cos\frac{\delta_a - \delta_b}{2}\sin\frac{\delta_a + \delta_b}{2} \tag{22}$$

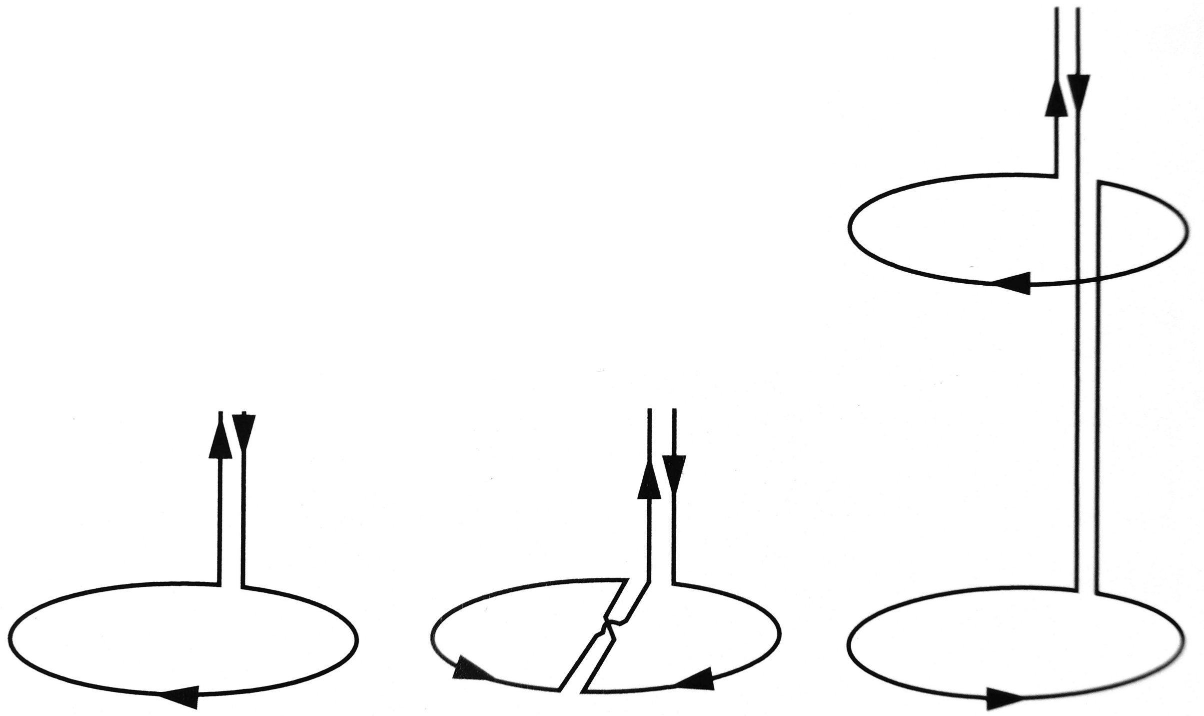
which leads to:

$$\delta_a - \delta_b = \frac{2e}{\hbar}\oint \vec{A}\cdot d\vec{s} = \frac{2e\Phi}{\hbar} = 2\pi\frac{\Phi}{\Phi_0} \tag{23}$$

with the magnetic flux quantum $\Phi_0 = \frac{h}{2e} = 2.07\,\mathrm{fTm}^2$.

Since the cosine term of the current I_s oscillates with the magnetic field, hitting the maxima for each surrounded magnetic flux quantum, the current is extremely sensitive to small changes of the magnetic field, so that even neuromagnetic signals can be measured (Ibach and Lüth, 2008).

To optimize the sensitivity, SQUIDs are very small, less than 1 mm in diameter. Unfortunately, this is why they couple badly to the magnetic field. To enhance coupling, flux transformers are used to collect more magnetic flux in one SQUID loop, such as magnetometer or gradiometer, see Fig. 2.12.



(a) Magnetometer **(b)** Planar gradiometer **(c)** Axial gradiometer

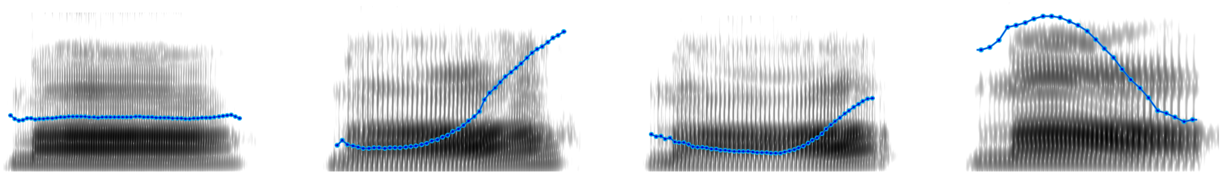
Figure 2.12: Flux transformer

Flux transformers are used to collect more magnetic flux in one SQUID loop, such as magnetometer or gradiometer. The magnetometer (a) consists of a single pick-up coil, which leads to a high sensitivity to sources nearby but also further away. To decrease the sensitivity to distant sources, compensation coils are included in the gradiometer (b) and (c) (Hansen et al., 2010, p.32)

The magnetometer consists of a single pick-up coil, which leads to a high sensitivity to sources nearby but also further away. To decrease the sensitivity to distant sources, compensation coils are included in the gradiometer. As the name already implies, the gradiometer measures the gradient of magnetic field rather than the magnetic field itself. It is thus insensitive to homogeneous fields (Hansen et al., 2010). The MEG that I used for my studies utilizes planar gradiometers. Their maximum signal is reached for sources underneath them (Hansen et al., 2010). Looking at the so-called top view of all gradiometers, which shows their distribution among the head in two dimensions as looking down from the top of one's head, thus illustrates considerably the locations of neural activation.

2.4. Neurolinguistic Background

Pitch is an important feature of speech that carries a wealth of linguistic and non-linguistic information (Plack et al., 2005). "Pitch is that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from high to low" (American National Standards Institute, 1994), a subjective measure that cannot be expressed directly in physical terms. It is linked to the fundamental frequency f_0.

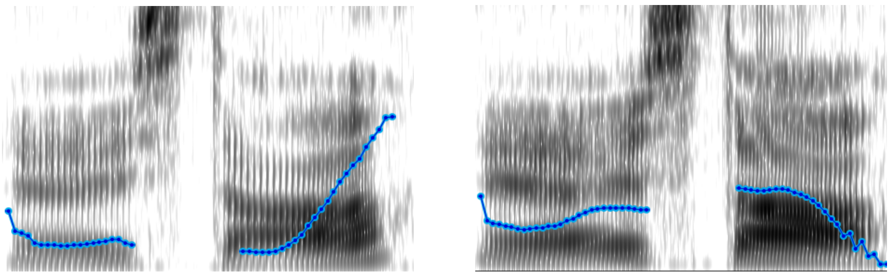


(a) Tone 1 **(b)** Tone 2 **(c)** Tone 3 **(d)** Tone 4

Figure 2.13: Spectrograms of Chinese tones
In Mandarin Chinese, there are four different tones (varying processes of frequency and intensity) that help distinguish between different meanings. Tone 1 has constant pitch and sound intensity. Tone 2 has rising pitch and sound intensity. Tone 3 first has falling but then rising pitch and sound intensity. Tone 4 has falling pitch and sound intensity.

In tonal languages, such as Mandarin Chinese, changes of the main frequency f_0, so-called "pitch-contours", are used to differentiate between meanings on a syllable level, see Fig. 2.13. In linguistics, they are called "tones", which might be confusing because in physics "tone" relate to only one constant frequency but in linguistics “tone” stands for a change of a complex sound with main frequency f_0 and harmonics over time.

Pitch contours in non-tonal languages however serve another purpose. They carry prosodic information, for example distinguish between questions and positive sentences, see Fig. 2.14.



(a) Question: “Er ist da?” **(b)** Positive Sentence: “Er ist da.”

Figure 2.14: Spectrograms of German intonation

Unlike in tonal languages, pitch contours in non-tonal languages serve a different purpose, i.e. they carry prosodic information. By changing the pitch contour, Germans can distinguish between questions (“Er ist da?” - He is there?) and positive sentences (“Er ist da.” - He is there.).

Various studies have investigated speech perception from neuroanatomical (Hackett and Kaas, 2004; Hickok, 2009) and neurophysiological perspectives (Diesch et al., 1996; Eulitz et al., 1995; Hewson-Stoate et al., 2006; Yrttiaho et al., 2008, 2010, 2011) but some of the main aspects are still not well understood (Nelken and Ahissar, 2006; Patterson and Johnsrude, 2008).

The hierarchical model of primate auditory processing assumes that early stages of the auditory pathway respond to both speech and non-speech sounds in a similar way by encoding sounds in a highly detailed representation (Popper and Fay, 1992). In contrast, at later stages processes are assumed to extract relevant information immediately and effortlessly to process sounds that are behaviorally meaningful. Neurophysiological evidence strongly suggests that the primary auditory cortex plays a pivotal role which works as a hub that serves multiple streams (Nelken et al., 1999; Nelken, 2008; Nelken and Bar-Yosef, 2008). At that level sound processing goes beyond simple representations of acoustical properties. With increasing distance from the primary auditory cortex, higher levels are suggested to reflect more abstract representations of sounds

(Scott and Johnsrude, 2003). Evidence for a selective behavior of primary auditory cortex is provided by neurophysiological recordings of Wollberg and Newman (1972) who observed that a group of neurons of the primary auditory cortex in the squirrel monkey responded selectively to species-specific calls.

This finding was corroborated by Wang et al. (2005) who registered sustained responses elicited by sinusoids, noise bursts, amplitude- and frequency-modulated sounds. They demonstrated that single neurons in primary auditory cortex, as well as neurons in lateral belt areas of awake marmoset monkeys, exhibit a sustained firing pattern when driven by their preferred stimulus. In contrast, non-preferred stimuli evoked only onset responses or no discharges at all. The authors pointed out that such an enhancement might result from intracortical processing within the same area as well as via efferent feedback connections from higher areas, see Fig. 2.15.

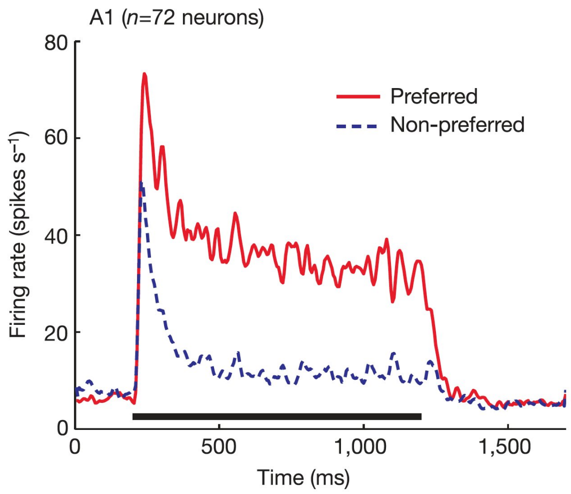


Figure 2.15: Preferred neurons of primary auditory cortex (Wang et al., 2005) Wang et al. (2005) demonstrated that single neurons in primary auditory cortex, as well as neurons in lateral belt areas of awake marmoset monkeys, exhibit a sustained firing pattern when driven by their preferred stimulus. In contrast, non-preferred stimuli evoked only onset responses or no discharges at all.

Although neurons at lower levels, such as the cochlear nucleus and the inferior colliculus, are believed to reflect the acoustic structure with extremely high fidelity, current studies on

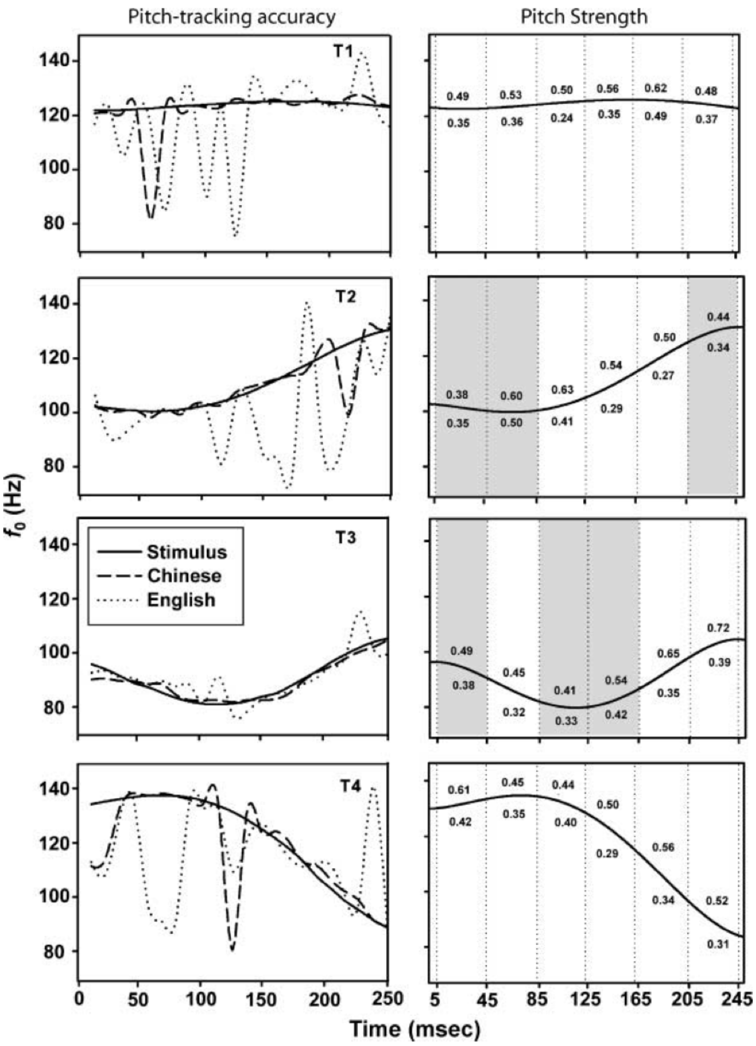


Figure 2.16: Frequency following responses (Krishnan et al., 2009a)

In a cross-linguistic study with Chinese and English participants Krishnan et al. (2009a) showed that pitch representations as reflected by FFR were stronger for Chinese subjects. This enhancement occurred irrespective of the linguistic or non-linguistic source of the sounds. The process is sensitive to specific pitch contours which are part of the native language.

frequency following responses (FFR), which are assumed to be generated at the level of the inferior colliculus or the lateral lemniscus (Skoe and Kraus, 2010), suggest that these stations are not merely passive relays during the transmission from periphery to higher stages along the auditory pathway. Instead, recent data show that these phase-locked responses are influenced by short-term and long-term experiences (Musacchia et al., 2007; Song et al., 2008). For example, Swaminathan et al. (2008) demonstrated in a cross-linguistic study with Chinese and English participants that pitch representations as reflected by FFR were stronger for Chinese subjects. However, this enhancement occurred irrespective of the linguistic or non-linguistic source of the sounds. Thus, the superior pitch-tracking accuracy of Chinese subjects is suggested to reflect some neural plasticity at early pre-attentive stages which presumably is shaped by specific spectro-temporal features of sounds instead of speech per se. Data of the same group (Chandrasekaran et al., 2009a,b; Krishnan et al., 2009a) provides evidence that this process is sensitive to specific pitch contours which are part of the native language, see Fig. 2.16. Further evidence that non-linguistic processes also induce more robust FFR is given by the comparison of musicians and non-musicians (Wong et al., 2007). There it was demonstrated that the stimulus-to-response correlation depended to a highly significant extent on their years of musical training. Taken together, these short- and long-term effects are in line with the assumption that the auditory corticofugal system is based on multiple feedback-loops (Suga, 2011). On the cortical level, such comparisons, including measures of sustained responses, are missing.

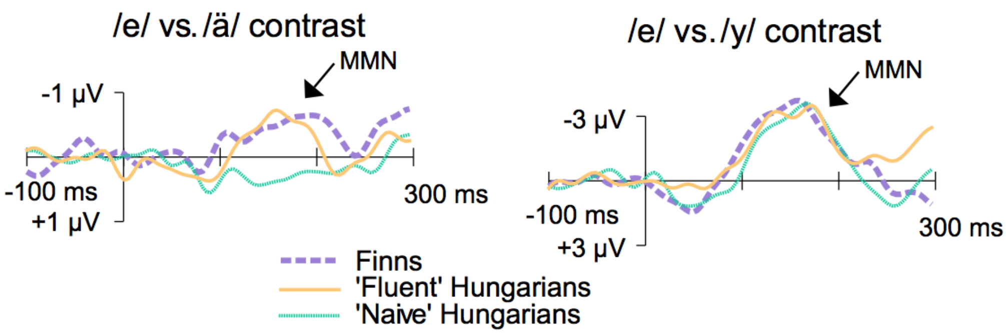
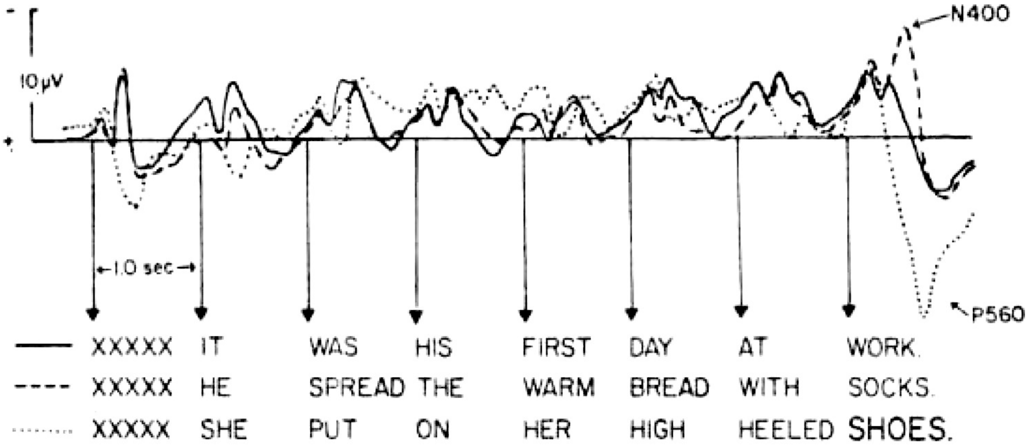


Figure 2.17: MMN and language learning (Näätänen et al., 2007)
The vowels /e/, /y/, /ä/ are part of the Finnish phoneme system, while only /e/, /y/ are part of the Hungarian phoneme system. Näätänen et al. (2007) showed that phonemes that occur in the subjects' mother tongue show larger MMN responses than those that do not occur there. Furthermore, their results indicate an effect of language learning because Hungarians who are fluent in Finnish ("fluent Hungarians") also show an enlarged MMN response compared to those who have not learnt Finnisch ("naive Hungarians").

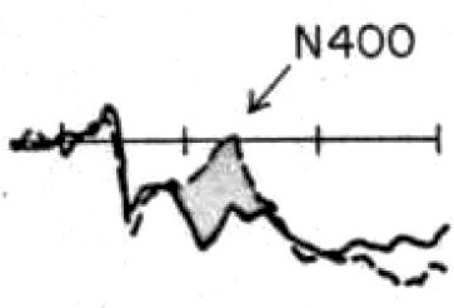
However, studies that investigated transient responses, such as the mismatch-negativity (MMN), showed that larger MMN responses were recorded in native speakers for phonemes that occur in Mandarin Chinese compared to Americans (Chandrasekaran et al., 2009a,b; Krishnan et al., 2009a). Similar effects have been also observed for other language groups as for Finish and Estonian (Näätänen et al., 1997), see Fig. 2.17 and also for lateralization effects in High Dutch and a Dutch dialect (Fournier et al., 2010). Already at 150 ms, an access to certain aspects of phonological categories is thus indicated with MMN (Phillips et al., 2000).

A recent neurophysiological study with combined magneto- and electroencephalographic recordings by Gutschalk and Uppenkamp (2011) revealed that the specific activity elicited by synthetic vowels and by non-linguistic regular sounds were located within the same area along the anterolateral Heschl's gyrus close to the primary auditory cortex. The authors concluded that early vowel and pitch processing does not occur in distinct fields within the auditory cortex, and more importantly, that early speech processing relies to some considerable extend on generators located in Heschl's gyrus. They conclude that the activity observed at the level of the superior temporal plane reflects processes involved in formant extraction.

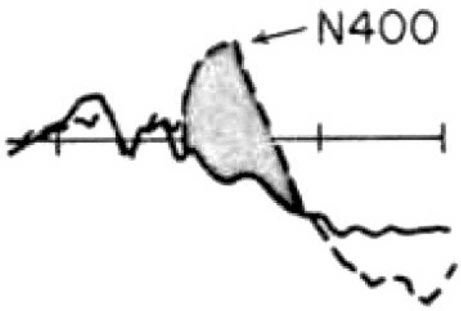
There is a component elicited by semantically inappropriate words in reading tasks which starts at ~ 250 ms, peaks at 400 ms and lasts until 600 - 800 ms, the so-called N400 (Kutas and Hillyard, 1980). Kutas and Hillyard (1980) used seven-word sentences with the last word being either semantically inappropriate with different degrees of inappropriateness, or semantically correct and expected, see Fig. 2.18. The N400 component was elicited when the sentence ended with an inappropriate word. Kutas and Hillyard (1980) suggest that the negative component was elicited because of expectations which were first built on the preceding six words and then disappointed by an inappropriate word leading to "a second look" or "reprocessing". Similar to this, Brown-Schmidt and Canseco-Gonzalez (2004) also found N400 effects in ERP for semantic abnormalities in tone or/and syllable for Mandarin Chinese speakers while listening to normal and abnormal sentences. Helenius et al. (2002) and Kujala et al. (2004) identified the N400 component to be associated with activation of the superior temporal cortex in the immediate vicinity of the auditory cortex. Kutas and Hillyard (1982), Boddy (1986) and Kutas et al. (1988) found the N400 to be larger over the right than left hemisphere.



(a) Classical N400 paradigm



(b) Moderate N400



(c) Strong N400

Figure 2.18: N400 effect in event-related potentials

Fig. 2.18(a) illustrates the classical N400 paradigm from Kutas and Hillyard (1980), who applied seven-word sentences with the last word being either semantically inappropriate with different degrees of inappropriateness, or semantically correct and expected. Moderately inappropriate or unexpected words (b) elicit a small N400, while strongly inappropriate words (c) elicit a larger N400. Kutas and Hillyard (1980) suggest that the negative component was elicited because of expectations which were first built on the preceding six words and then disappointed by an inappropriate word leading to “a second look” or “reprocessing”.

3. Methods

In this section, the stimuli are presented with their individual characteristics such as sound intensity, pitch contours, and spectra, see Sec. 3.1. The recording of these stimuli are also introduced. Then, details of the data acquisition are considered, see Sec. 3.2, as well as the tools that were chosen for data analysis, see Sec. 3.3.

3.1. Stimuli

In the first part of the study which included all linguistic stimuli, 20 German and 20 Chinese speakers participated. The linguistic stimuli were presented in two different sessions, with eight stimuli for each part. One session consisted of the syllables /ma/ and /mu/, see Fig. 3.1 and 3.2, represented for all four tones, which lasted 28 min. The other session consisting of the vowels /o/ and /ö/, which were also represented for all four tones, lasted 22 min in total, see Fig. 3.3 and 3.4. All the syllables /ma1/-/ma4/ as well as the syllables /mu2/-/mu4/ are meaningful in Chinese, only /mu1/ does not contain any meaning in Chinese, see Tab. 3.1. The vowels /o/ and /ö/ are both part of the German phonetic system, while /ö/ does not occur in Chinese. To avoid habituation as systematic error, we started half the experiments with the syllable-stimulation and the other half with the vowel-stimulation.

	Chinese	Pinyin	English	Chinese	Pinyin	English
Tone 1	妈	ma1	Mom	–	mu1	–
Tone 2	麻	ma2	cannabis	模	mu2	form
Tone 3	马	ma3	horse	母	mu3	mother
Tone 4	骂	ma4	to rant	木	mu4	wood

Table 3.1: Linguistic stimuli /ma/ and /mu/

Some examples of the syllables /ma/ and /mu/ are shown with their Chinese characters, the phonetic spelling called pinyin and their English translation. All the syllables /ma1/-/ma4/ are meaningful in Chinese as well as the syllables /mu2/-/mu4/, only /mu1/ does not contain any meaning in Chinese.

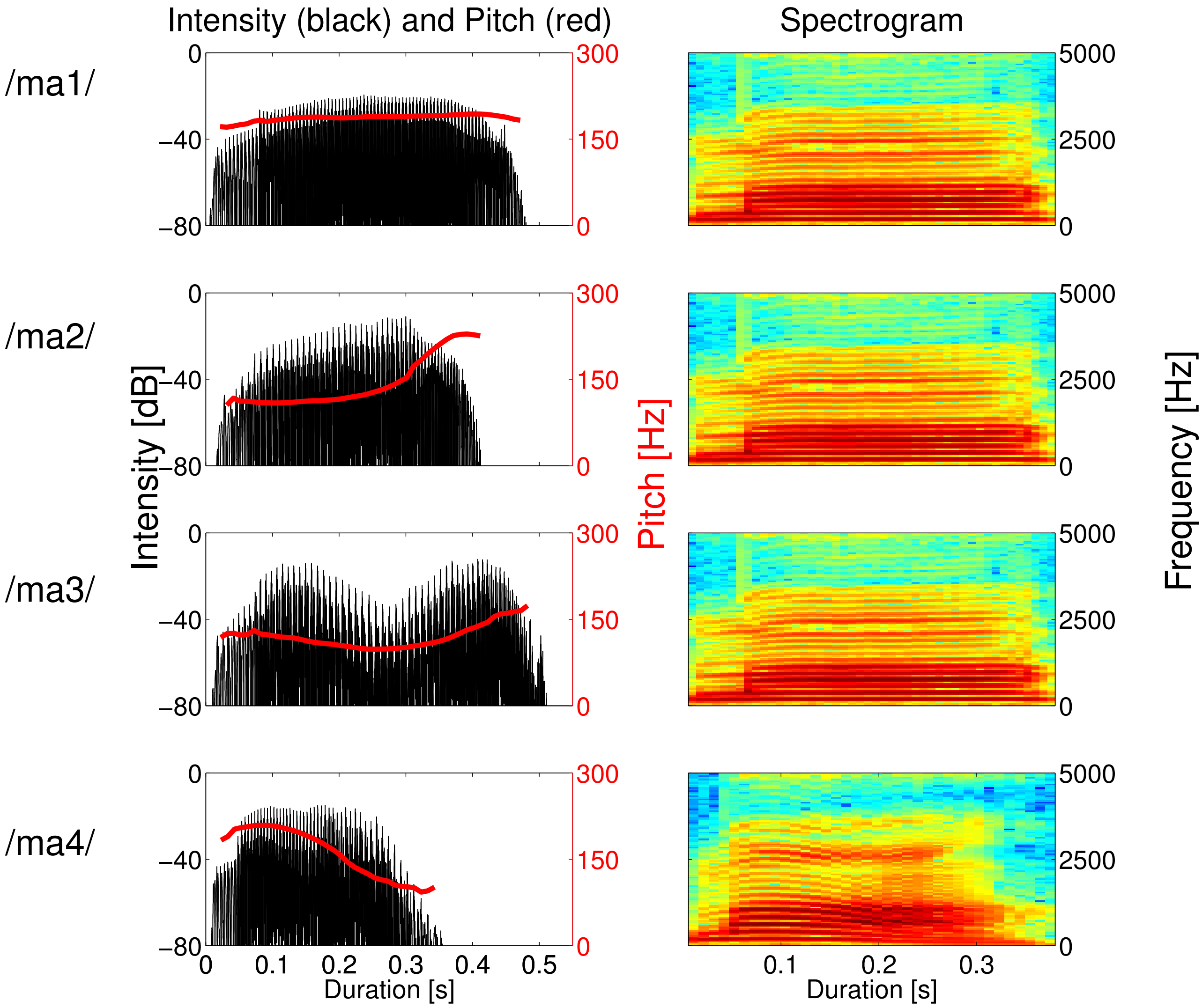


Figure 3.1: Characteristics of stimuli /ma/

This figure displays the sound intensity (black), pitch contour (red) and spectrogram (colored with red – high intensity, blue – low intensity) of the syllables /ma1/-/ma4/ which are meaningful in Chinese. The syllable /ma1/ has constant pitch and sound intensity and means "Mom". /ma2/ has rising pitch and sound intensity and means "canabis". /ma3/ first has falling but then rising pitch and sound intensity and means "horse". /ma4/ has falling pitch and sound intensity and means "to rant".

In the second part, 14 German and 11 Chinese subjects who also participated in the first part were included. The stimuli consisted of the syllable /ma1/ and a French horn tone (b-flat, $f_0 = 117$ Hz), see Fig. 3.5. Thus, the session only lasted 8 min. It was included between the

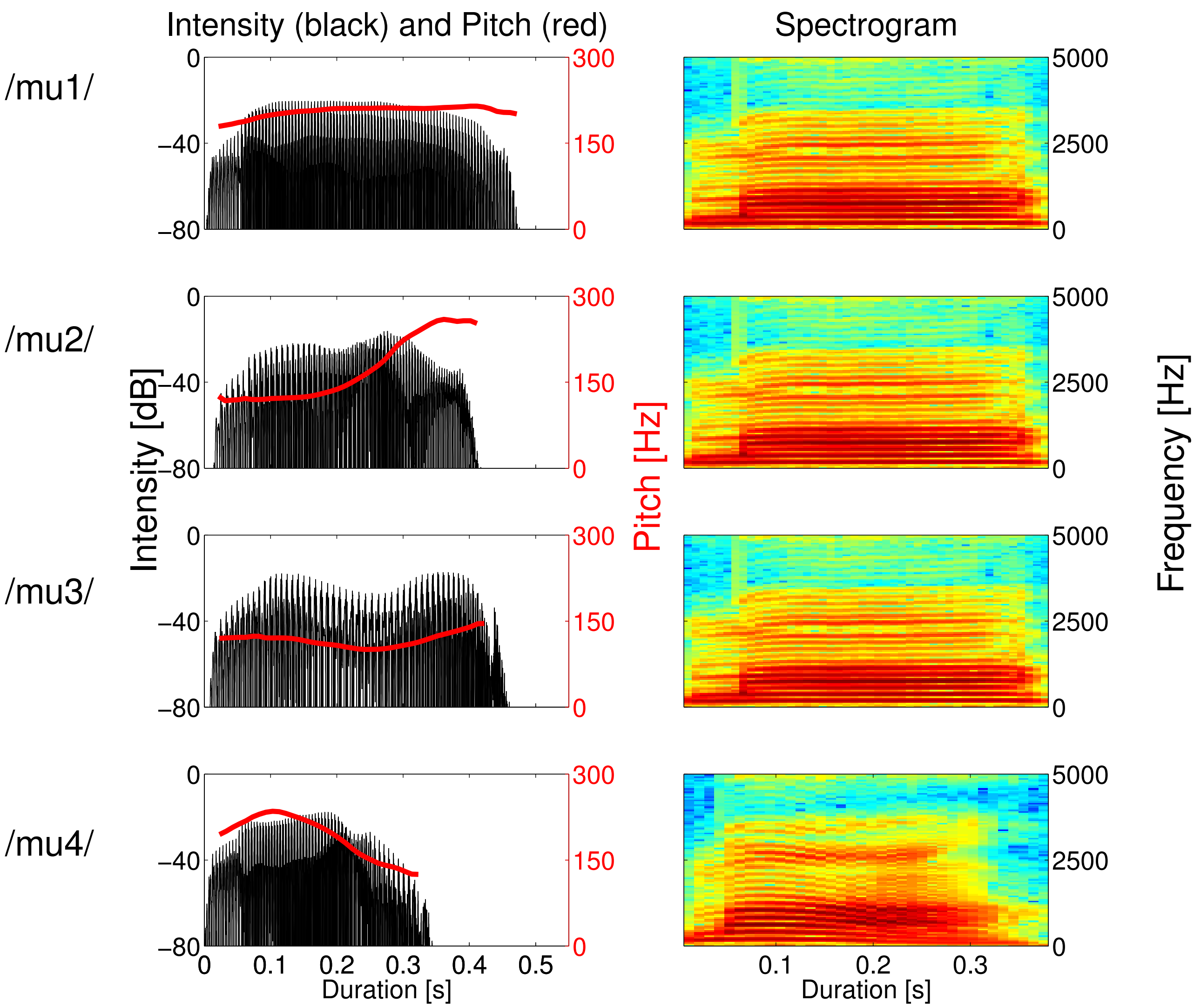


Figure 3.2: Characteristics of stimuli /mu/

This figure displays the sound intensity (black), pitch contour (red) and spectrogram (colored with red – high intensity, blue – low intensity) of the syllables /mu1/-/mu4/. Only the syllables /mu2/-/mu4/ are meaningful in Chinese. /mu1/ has constant pitch and sound intensity and does not contain any meaning. /mu2/ has rising pitch and sound intensity and means "form". /mu3/ first has falling but then rising pitch and sound intensity and means "mother". /mu4/ has falling pitch and sound intensity and means "wood".

other two linguistic sessions for the above mentioned subjects.

In Fig. 3.1-3.5, the intensities (black), pitch contours (red), and spectrograms (colored) of all stimuli are displayed. The spectrograms display the color-coded sound intensity (red – high

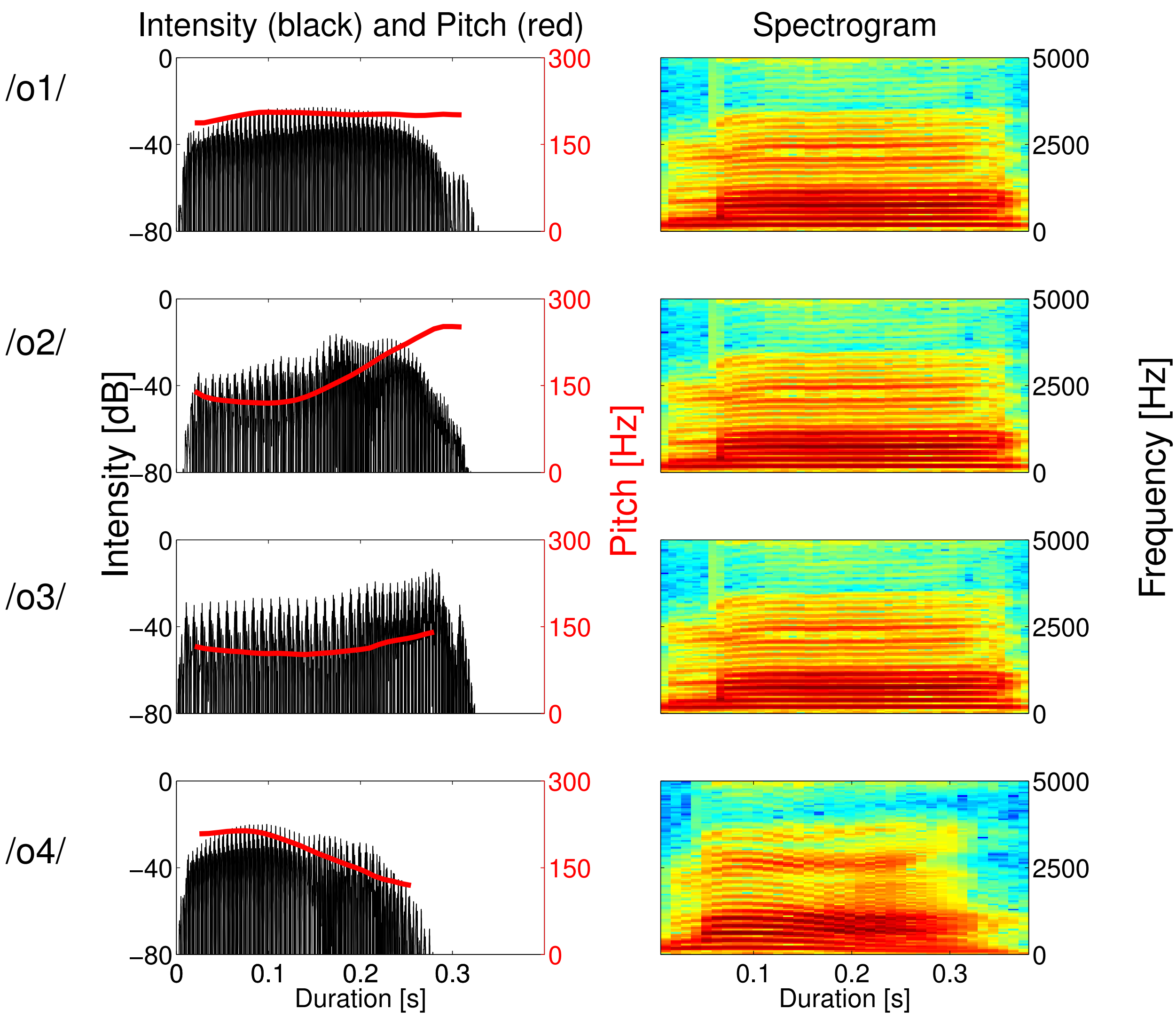


Figure 3.3: Characteristics of stimuli /o/

This figure displays the sound intensity (black), pitch contour (red) and spectrogram (colored with red – high intensity, blue – low intensity) of the vowels /o1/-/o4/ which are part of the Chinese phonetic system but they do not contain any meaning. Tone 1 has constant pitch and sound intensity. Tone 2 has rising pitch and sound intensity. Tone 3 first has falling but then rising pitch and sound intensity. Tone 4 has falling pitch and sound intensity.

intensity, blue – low intensity) among frequency over time. The frequency bands with high intensity are called formants. They are characteristic for the speaker and are also required to distinguish between vowels. The syllables /ma/ and /mu/, as well as the vowels /o/ and /ö/ were matched for each tone with respect to duration and similar intensity and pitch contours

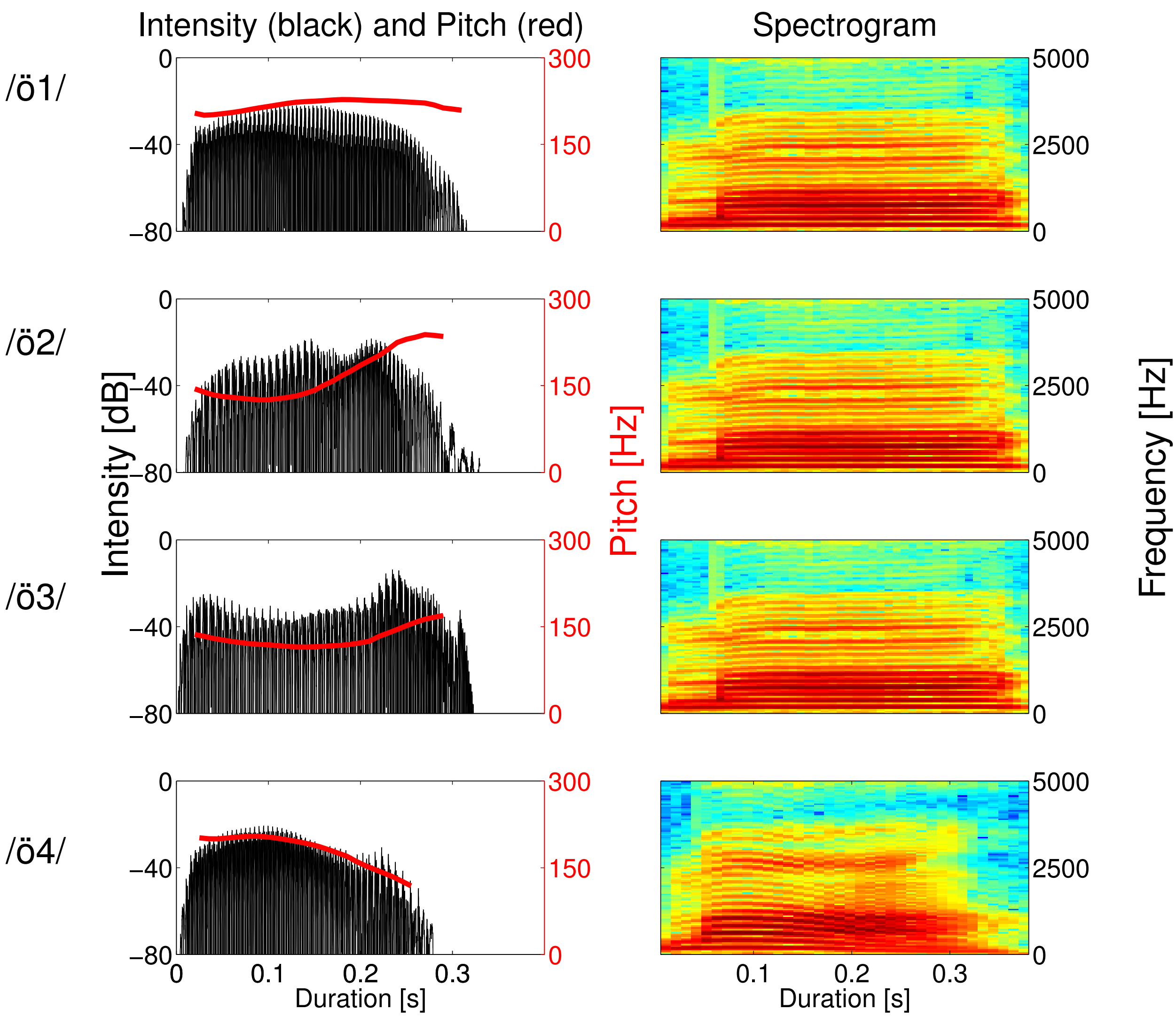


Figure 3.4: Characteristics of stimuli /ö/

This figure displays the sound intensity (black), pitch contour (red) and spectrogram (colored with red – high intensity, blue – low intensity) of the vowel /ö/ which is part of the German phonetic system but is not part of the Chinese phonetic system. Nevertheless, we added Chinese tones to this vowel. Tone 1 has constant pitch and sound intensity. Tone 2 has rising pitch and sound intensity. Tone 3 first has falling but then rising pitch and sound intensity. Tone 4 has falling pitch and sound intensity.

to make comparable pairs of stimuli for later analysis. In order to examine speech perception in the human brain, we used natural speech stimuli but the downfall with this is the lack of control over all attributes. Thus, the stimuli do not have the same length, pitch or formants for

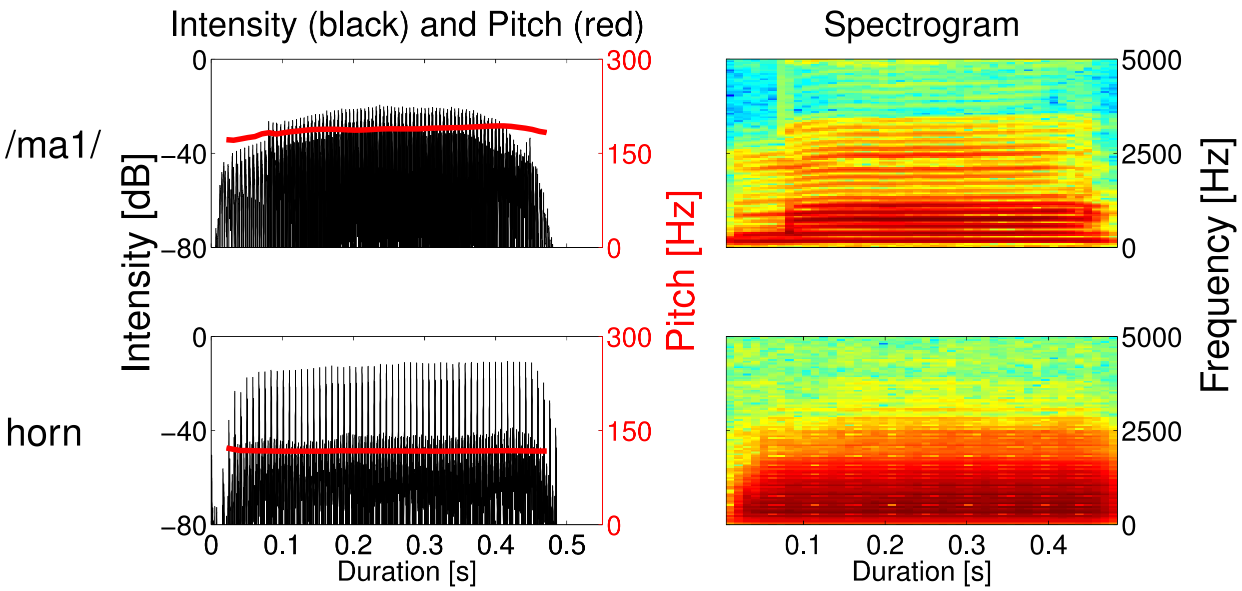


Figure 3.5: Characteristics of stimuli /ma1/ and horn

This figure displays the sound intensity (black), pitch contour (red) and spectrogram (colored with red – high intensity, blue – low intensity) of the linguistic stimulus /ma1/ and the musical stimulus of a horn tone. The syllable /ma1/ was chosen because it matches the horn tone the best. Both of them have the same stimulus length of 493 ms, constant pitch and sound intensity, although the average main frequency of the horn is lower (f_{horn} = 117 Hz) than the linguistic stimulus (f_{ma1} = 187 Hz).

all tones. Syllables are by nature longer than vowels because they have a consonant in front of the vowel. Tone 4 is by nature the shortest in comparison, while tone 3 is the longest. That is the reason why we matched pairs of stimuli for each tone. For each tone, the syllables /ma/ and /mu/ have very similar pitch and sound intensity progresses, as can be seen in Fig. 3.1 and 3.2, and so do the vowels /o/ and /ö/, see Fig. 3.3 and 3.4. Besides, the linguistic stimulus /ma1/ from Exp. 1 was chosen for the second experiment because it matches the horn tone the best, see Fig. 3.5. Both of them have constant pitch and sound intensity, although the average main frequency of the horn is lower (f_{horn} = 117 Hz) than the linguistic stimulus (f_{ma1} = 187 Hz).

All subjects were measured under the same passive conditions, while watching a silent movie of their choice. We used disposable foam ER3-earphones for all subjects, as illustrated in Fig. 3.6. The spectra of the stimuli /o/ and /ö/ are displayed in Fig. 3.7, which show that the ER3-

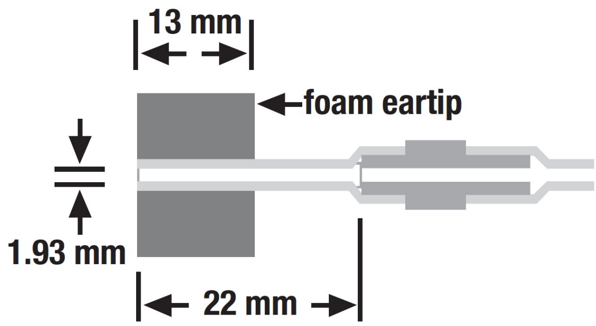
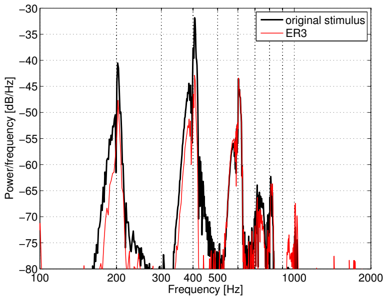


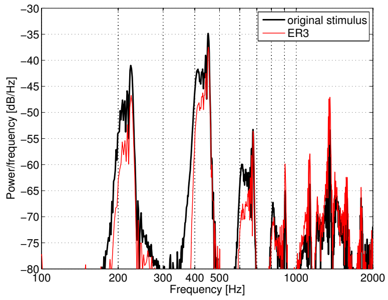
Figure 3.6: ER3-earphones

We used disposable foam ER3-earphones for all subjects's measurements. The foam is squeezed together by the subjects' fingers and inserted into the ear canal, where it then adapts to the individuals.

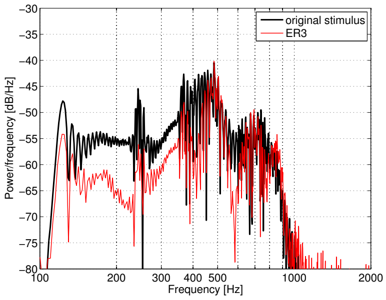
earphones leave a sufficiently rich spectrum of the original stimuli to the subjects' sensitive area of kHz range. During preparation we made sure that the ER3-earphones did not dramatically change the sound quality of our speech stimuli. The stimuli were still recognizable as natural speech. In fact, barely any difference between the original stimuli and the sound from the ER3-earphones could be noticed. The Chinese speakers perceived meanings from the syllable paradigm as single words but not as sentences, while they did not make sense out of the vowel paradigm as they did not perceive any meaning. Another reason why these stimuli are well perceived is the ability of the human brain to reconstruct missing fundamental frequencies to the overall spectra as it happens in telephone conversations. Male human voices typically have a fundamental frequency of $f_0 = 150$ Hz and they are still recognizable as such even though telephones only pass frequencies above 300 Hz (Moye, 1979). The spectra were recorded using the oscilloscope Tektronix TDS 2012B.



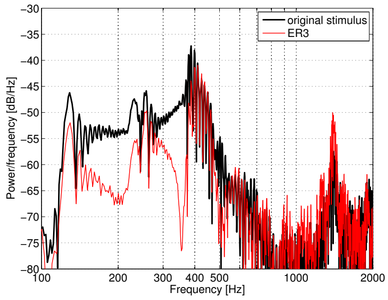
(a) /o1/



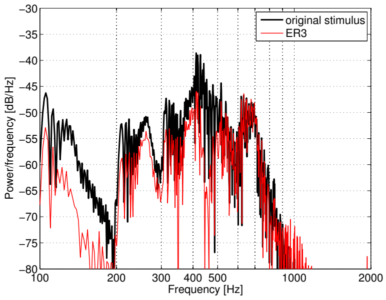
(b) /ö1/



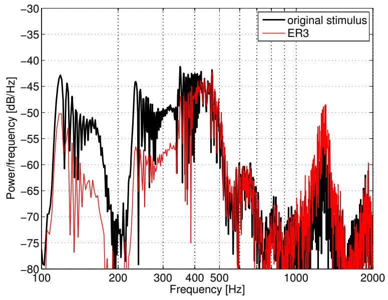
(c) /o2/



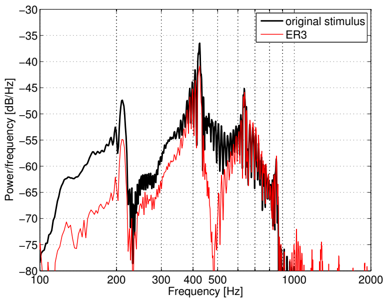
(d) /ö2/



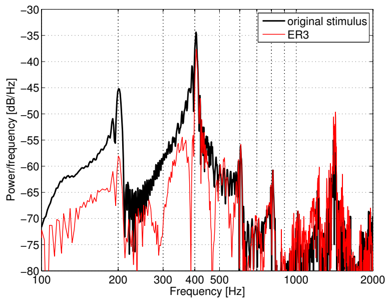
(e) /o3/



(f) /ö3/



(g) /o4/



(h) /ö4/

Figure 3.7: Spectra of stimuli

The black curves show the spectra of the recorded stimuli, while red shows the spectra of the sounds coming out of the ER3 earphones. The spectra depicts that the ER3-earphones leave a sufficiently rich spectrum of the original stimuli to the subjects' sensitive area of kHz range.

Recording of Stimuli All linguistic stimuli were spoken by a male native Chinese speaker who also speaks German fluently. The stimuli were recorded inside an echo-free chamber as mono wav-files with the free software "Audacity 1.3 beta", using a sampling rate of 48 kHz. The original wav-files were cut into single stimuli. All stimuli were normalized to have the same total intensity of 72 dB SPL. For each tone, the vowel stimuli /o/ and /ö/ as well as the syllables /ma/ and /mu/ were chosen to match each other with regard to their duration and similarity of pitch contours. The final choice was made on the grounds of sound quality and clearness of speech.

In Fig. 3.8 and 3.9 the setting of our stimuli recording is displayed. The linguistic stimuli were recorded using the capacitor microphone Type 4193 from Brühl&Kjaer, utilizing the preamplifier from Brühl&Kjaer as well as the mixing table Mäckie Type 1402-VLZ Pro, the Audio interface RME Hammerfall DSP Multiface, and a Dell Latitude D830 Laptop to run the recording software.

Figure 3.8: Recording of linguistic stimuli

All linguistic stimuli were recorded inside an echo-free chamber.

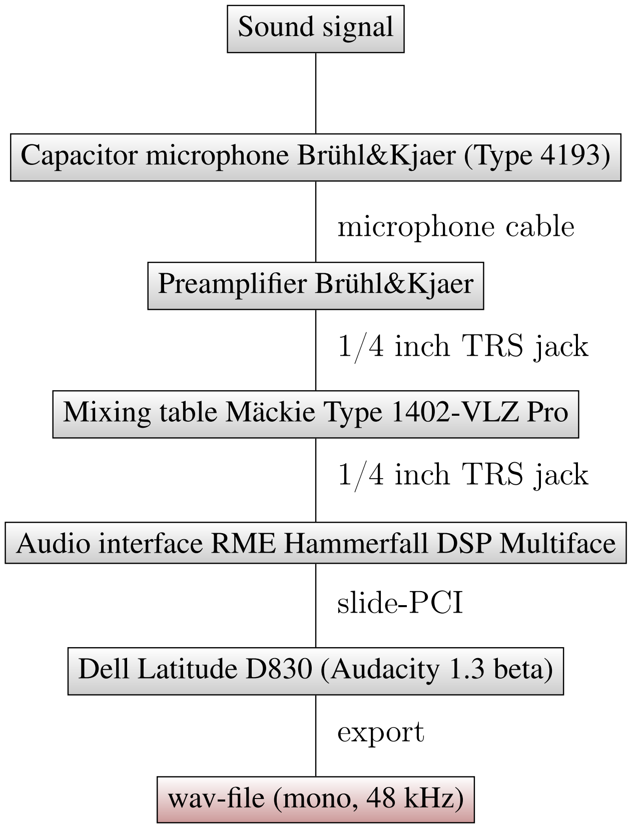


Figure 3.9: Settings of stimuli recording

Inside an echo-free chamber, the linguistic stimuli were recorded using the capacitor microphone Type 4193 from Brühl&Kjaer, utilizing the preamplifier from Brühl&Kjaer as well as the mixing table Mäckie Type 1402-VLZ Pro, the Audio interface RME Hammerfall DSP Multiface, and a Dell Latitude D830 Laptop with the software "Audacity 1.3 beta". The original graph was provided by Martin Andermann who also helped with the recording.

3.2. Data Acquisition

Data acquisition was performed using the Neuromag-122-whole-head-MEG-system of the MEG laboratory of the Neurological Department of the University of Heidelberg. 122 gradiometers inside the MEG simultaneously measure the gradient of the magnetic field. In my experiments, we applied the maximum sampling rate of the system, 1 kHz, and the full bandwidth of 0 - 330 Hz. Each MEG session consisted of several stimuli with each stimulus being represented 200 times in random order. 3-7 noisy channels, known to the MEG setting on the day of measurement, were excluded beforehand.
20 native German (8 female, 12 male) and 20 native Chinese (18 female, 2 male) speakers participated in the studies. The Germans ranged from 23 to 74 years, with a mean ($\pm$Std. Dev.) of 33.8 ± 13.4 years. The Chinese ranged from 20 to 34 years, with a mean of 23.7 ± 3.4 years.

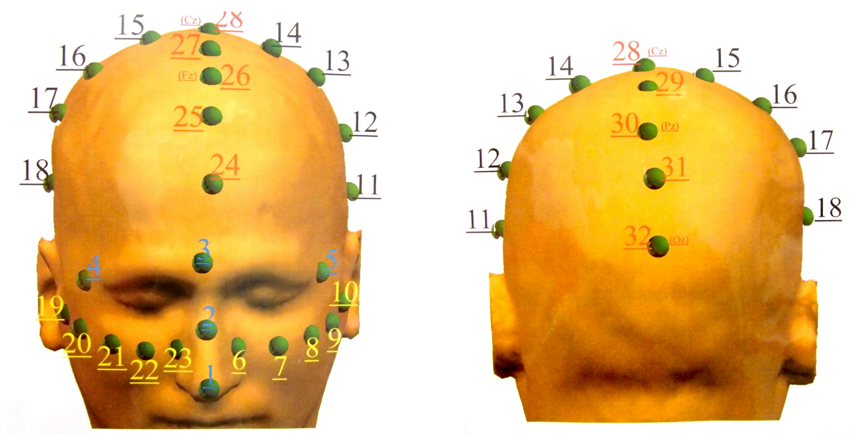


Figure 3.10: Digitalization of subjects' head
To obtain the subjects' form and size of head, 32 reference points are used, as depicted in these graphs.

With the help of four coils, which are attached to distinct points on the scalp with the help of double-sided adhesive tape, the head position is determined. Two were placed behind the earlobes, as high as possible because it should be covered by the MEG sensors and two were placed at the forehead, at the receding hairline. All coils should be covered by the MEG sensors and placed as far away from each other as possible. They should also stick to the scalp, not the hair. In order to obtain the subjects' form and size of head, each subject's head was digitalized with 32 reference points, as depicted in Fig. 3.10. If co-registration was performed on the subject when using MRI, the exact dipole localization within the subject's head could be determined (Hansen et al., 2010).

3.3. Data Analysis

The data analysis was performed offline by using the software BESA 5.1 (BESA GmbH Germany), assuming a spherical head model with homogenous volume conductor. Remaining noisy data of gradiometers left in the raw data were removed. Even though the subjects were told to sit as still as possible, movement artifacts such as yawning and finding other sitting positions had to be excluded by looking at the raw data. Other artifacts, such as epochs with amplitudes larger than 8000 fT/cm or gradients larger than 800 fT/(cm ms) were also excluded. After this, around 180 sweeps remained for each subject and condition, which were averaged from -300 ms to 1000 ms with 0 ms as the stimulus onset. The baseline was set to the average signal level between -100 and 0 ms.

There are different methods how to perform data analysis. For this dissertation, the root-mean-square (RMS) of the magneto-gradiometers, a 2-dipole and a 4-dipole model were applied with the main focus of this dissertation on the dipole analysis.

In the following paragraphs, the filenames of the data output are included schematically in order to give the interested reader some hints to understand the files on the enclosed CD. The filenames are added in round brackets, using a different font.

Root-Mean-Square (RMS) The root-mean-square (RMS) of the magneto-gradiometers is a model-independent tool for data analysis. For this, the direct signals from the gradiometers are obtained by adding the exported model output Mod_i (`subj/Mod-cond.avr`) and residual output Res_i (`subj/Res-cond.avr`) from BESA: $G_i = Mod_i + Res_i$ with i being the index of the gradiometer. The RMS is calculated by taking the square-root of the sum of squared signals over all gradiometers:

$$RMS(t) = \sqrt{\sum_i G_i^2(t)}. \tag{24}$$

Thus polarity does not play any role in this method. But this also represents a downfall because components of different polarity which are very close to each other cannot be differentiated using the RMS. It thus serves as an additional tool to reassess the results from the dipole analysis.

Dipole Models The main focus of our data analysis is the application of dipole models. The dipoles are adjusted to simulate the measured magnetic fields as good as possible by using the software BESA. To obtain potentials and fields from given sources is straightforward, see Sec. 2.3. The reconstruction of the exact distribution of current sources within the head from the measured potentials or fields is called inverse problem, for which Helmholtz has already shown in 1863 that there is no unique solution because of non-vanishing volume currents that do not give any signals outside the head. In spherically symmetric heads, radial currents do not create any magnetic field outside the head. But since we expect the main activity in the auditory cortices where the primary currents are mostly tangential, there is hopefully only little to be missed. Thus, we made a two dipole model, assuming that the magnetic field was created by one dipole in each hemisphere.

A principal component analysis (Berg and Scherg, 1994) was also performed over the last few milliseconds of the unfiltered condition to compensate drift and low frequency artifacts. The PCA component accounting for the most variance in this interval was added to the model for each condition and subject.

A typical dipole waveform with its typical transient (P1, N1, P2) and sustained components (SF) can be seen in Fig. 3.11. Each subject's fits are obtained by finding the best dipole adjustment in BESA for each component to simulate the measured magnetic field, which means the residual variance for the fit is reduced to its minimum. This minimum of residual variance (RV_{min}) is a measure of the goodness of fit. It is determined by

$$RV_{min} = \frac{\sum\limits_{t=t_{min}}^{tmax} \sum\limits_{i} Res_i^2(t)}{\sum\limits_{t=t_{min}}^{tmax} RMS^2(t)}. \qquad (25)$$

The fitting intervals around the peaks were determined from baseline to baseline around each peak, which resulted in the following approximate fitting intervals: $\sim 50 \pm 20$ ms for P1, $\sim 110 \pm 20$ ms for N1, $\sim 250 \pm 30$ ms for P2, and $\sim 450 \pm 150$ ms for SF. For our data analysis,

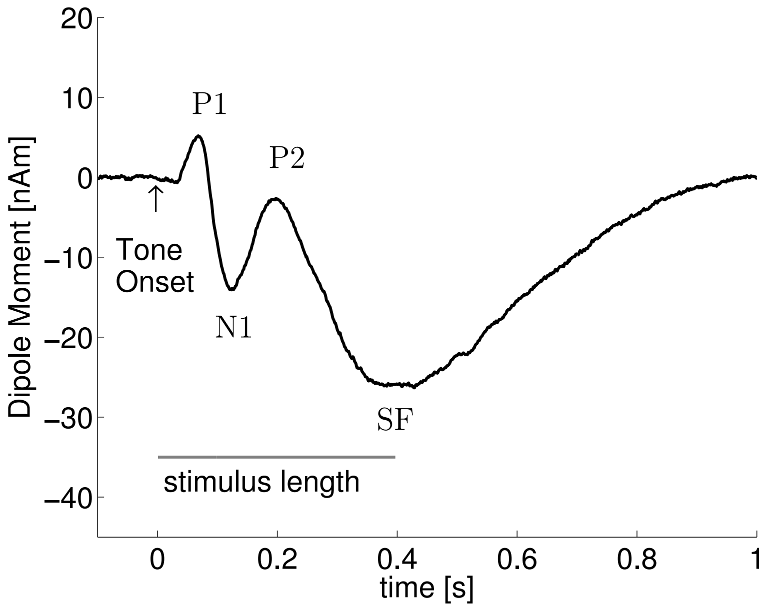
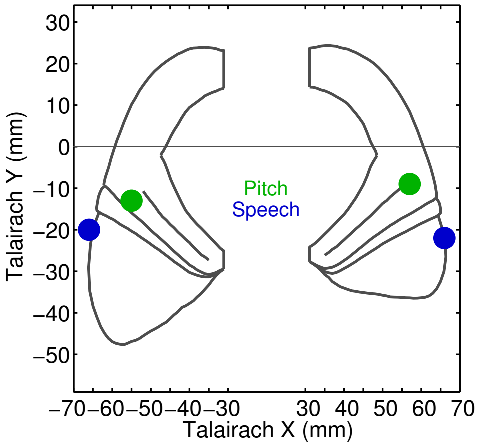


Figure 3.11: Typical dipole waveform (late latency auditory evoked potentials)
P1, also called P30 and P50, the first positive peak, which occurs at around 50 ms after the onset
N1, also called N100 is the first negative peak, which occurs at around 100 ms after the onset
P2, the second positive peak, occurring at around 250 ± 50 ms
SF, sustained field, starting at approximately 300 ms; its peak is at the end of the stimulus' length.

we evaluated all components, as well as the integrated sustained field (ISF) over the period of 300 to 1000 ms of the SF fit. This was done to exclude the influence of transient signals on the sustained field.

The unfiltered source waveforms (`subj/cond-fit.swf`) and their according Talairach coordinates (`subj/cond-fit.bsa`) for each fit, condition, and subject were exported to the software Matlab 7.7.0.471 (R2008b Student Version) by TheMathWorks Inc (USA) for further data analysis.

4-Dipole Model To evaluate the neural activation in different regions that are known for their high activation in fMRI to pitch paradigms, such as a bilateral region in lateral Heschl's gyrus (Patterson et al., 2002), and to speech paradigms, such as the superior temporal sulcus for vowel to non-speech contrasts (Kaas et al., 1999; Uppenkamp et al., 2006), I applied a 4-dipole model to our data analysis with fixed locations to these mentioned pitch and speech locations, as can be found in Fig. 3.12.



Talairach coordinates [mm]

	left hemisphere			right hemisphere		
	x	y	z	x	y	z
Pitch	−55	−13	+2	+57	−9	−2
Speech	−66	−20	0	+66	−22	−2

Figure 3.12: Talairach coordinates of the 4-dipole model

The coordinates are extracted from fMRI studies. The bilateral region in lateral Heschl's gyrus is known for high neural activation to pitch paradigms (Patterson et al., 2002), while the superior temporal sulcus is known for high activation for speech paradigms, such as vowel to non-speech contrasts (Kaas et al., 1999; Uppenkamp et al., 2006).

Statistics All data are shown as means ± standard error of mean.

Comparison of two groups was analyzed using unpaired two-tailed Student's t-test because the groups are independent and because the point of interest is the significance of the difference between groups. We tested $H_0 : \bar{x}_1 = \bar{x}_2$ against $H_1 : \bar{x}_1 \neq \bar{x}_2$ with $\bar{x}_1$ and $\bar{x}_2$ as the mean values from group 1 and 2. The degree of freedom is $\nu = n_1 + n_2 - 2$ with n_1 and n_2 as the amount of subjects in each group and $t(\nu) = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$ with σ_1 and σ_2 as the standard deviation of group 1 and 2 (Mittag, 2012).

For the intragroup comparison we used paired two-tailed Student's t-tests because certain characteristics are dependent on the subject and because the point of interest is the significance of the difference within one group. We tested $H_0 : \bar{x}_{c_1} = \bar{x}_{c_2}$ against $H_1 : \bar{x}_{c_1} \neq \bar{x}_{c_2}$ with $\bar{x}_{c_1}$ and $\bar{x}_{c_2}$ as the mean values of the characteristics of the same group. The degree of freedom is $\nu = n - 1$ with n as the amount of subjects and $t(\nu) = \frac{\bar{x}_{c_1} - \bar{x}_{c_2}}{\sigma_{c_1 - c_2}/\sqrt{n}}$ with $\sigma_{c_1 - c_2}$ as the standard deviation of the difference between both characteristics (Bortz et al., 2010).

4. Results

This section deals with the results from the MEG measurements of the mentioned paradigms from Sec. 3.1. The first part included all linguistic stimuli with the syllables /ma/ and /mu/ in one session and with the vowels /o/ and /ö/ in the other session, while the second part compared the linguistic stimulus /ma1/ with the non-linguistic stimulus of a French horn tone. For more details regarding the paradigms and stimuli, see Sec. 3.1.

I will start with the most essential result of the dissertation, the language effect of the sustained field (Sec. 4.1). Within the subsection about sustained field, I will give more details of the linguistic stimuli concerning lateralization, localization of dipoles, distribution, phonetic and semantic effects, as well as the effect of filtering (Sec. 4.1.1). Then the results of the paradigm concerning linguistic and non-linguistic stimuli will be discussed (Sec. 4.1.2). After that, the transient components (P1, N1, P2) as well as the sustained component (SF) of both groups will be thoroughly considered (Sec. 4.2). At last, the results of an individual MEG and EEG measurement will be discussed in Sec. 4.3.

For more details regarding the tools of data analysis, such as dipole models, RMS, and statistics, please refer to Sec. 3.3.

4.1. Sustained Field

As described earlier in Sec. 3.3, mainly a 2-dipole model was used for data analysis. Two effective dipoles, one in each hemisphere, were freely fitted to certain components, such as the sustained field. The SF fit was performed in the time interval from 300 to 600 ms after stimulus onset.

For a better evaluation of the sustained field, we integrated the dipole waveforms over the time interval of 300 to 1000 ms to exclude the influence of transient signals. The result is thus called integrated sustained field (ISF).

In Fig. 4.1, we have collected the average dipole waveforms for all stimuli. The integrated sustained fields (ISF) of the Chinese (red) are for all responses to linguistic stimuli significantly larger than those of the Germans (black).

For the first 16 linguistic stimuli, 20 native Chinese and 20 native German speakers were measured, while for the horn tone, a subgroup of 11 Chinese and 14 German subjects were

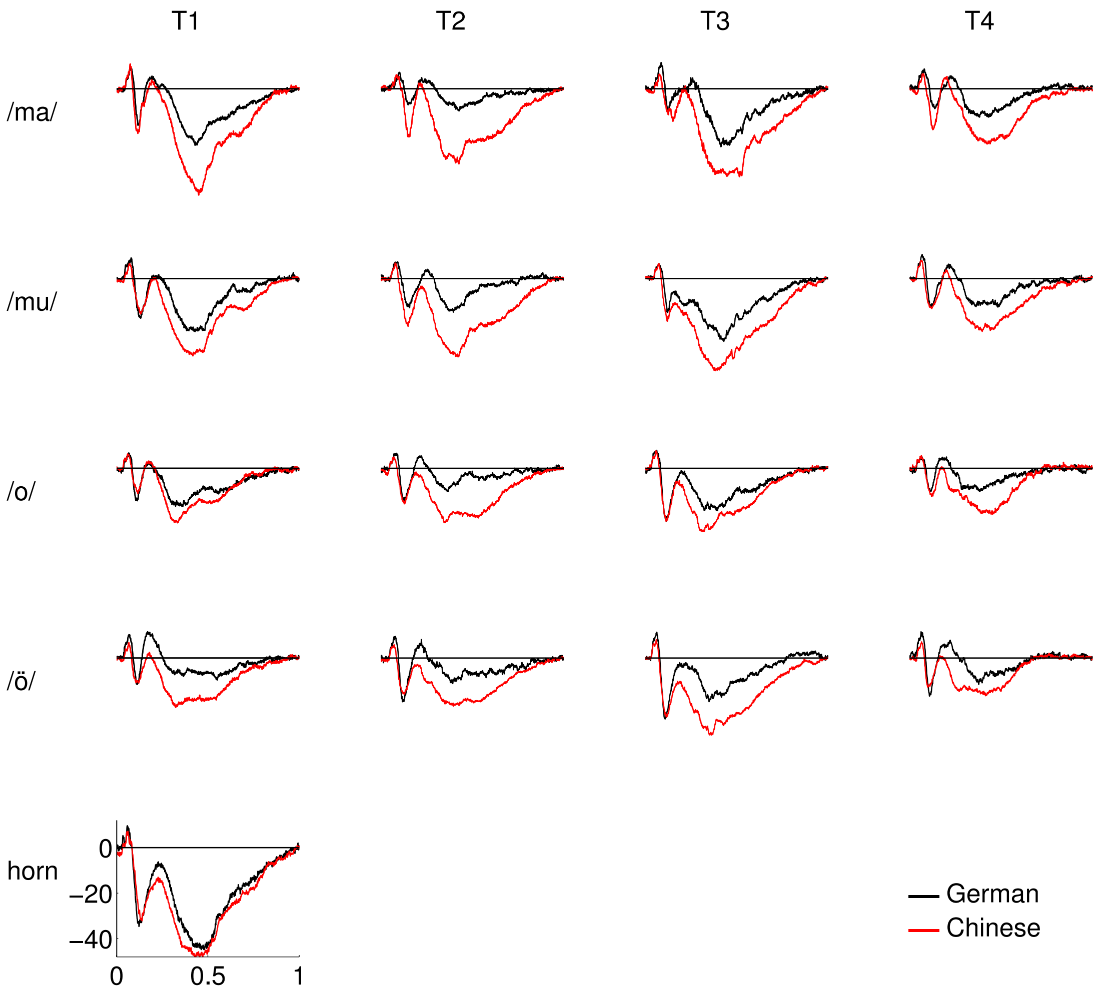


Figure 4.1: Dipole waveforms of Chinese and German subjects for each stimuli
For the first 16 linguistic stimuli, 20 native Chinese and 20 native German speakers were measured. The Chinese group consistently shows larger sustained fields than the German group. Only for the non-linguistic stimulus, the French horn, the ISF of both groups is approximately the same size. For this purpose a subgroup of 11 Chinese and 14 German subjects were measured.

measured.

4.1.1. Linguistic Stimuli

For all linguistic stimuli, including all syllables /ma/ and /mu/, vowels /o/ and /ö/ and tones 1-4, the Chinese group consistently shows larger sustained fields than the German group, as can be seen in Fig. 4.1 for the first 16 stimuli.

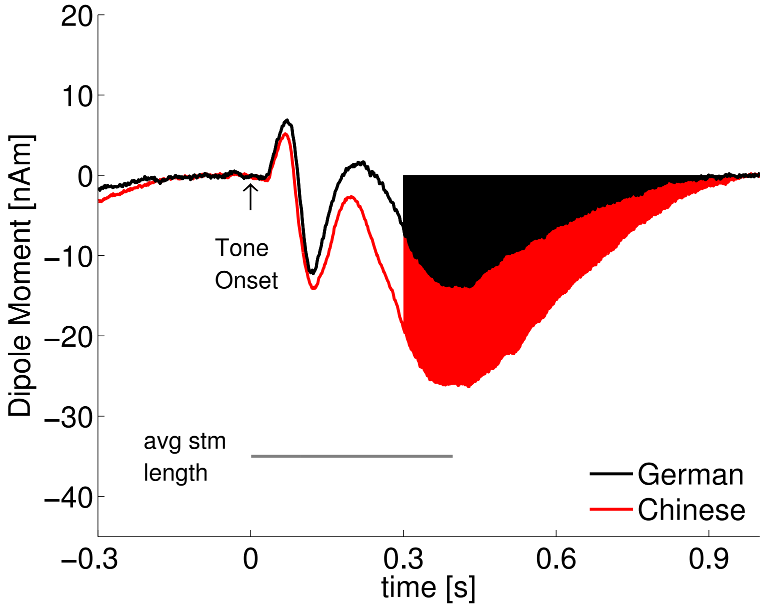


Figure 4.2: Average integrated sustained field of Chinese and German subjects Taking together all dipole waveforms for the linguistic stimuli, the Chinese subjects show an ISF of $ISF_{Chinese} = -9.1 \pm 1.0\,\text{nAm} \cdot \text{s}$ which is about double the size of the German subjects' ISF ($ISF_{German} = -4.1 \pm 1.3\,\text{nAm} \cdot \text{s}$). The difference between the groups is highly significant (t(38)=3,1; P=0.004)

In Fig. 4.2, the average over all linguistic stimuli is displayed which illustrates distinctly that the Chinese subjects' integrated sustained field is more than twice as big as that of the German subjects ($ISF_{Chinese} = -9.1 \pm 1.0\,\text{nAm} \cdot \text{s}$ and $ISF_{German} = -4.1 \pm 1.3\,\text{nAm} \cdot \text{s}$). The difference is highly significant ($t_{dip}(38) = 3.1$, $P_{dip} = 0.004$). The model independent root-mean-square of the gradiometers, see Fig. 4.3 and Table 4.1, fully confirms the results of the dipole fit. The Chinese subjects show an integrated sustained field of $ISF_{RMS,Chinese} = 3.6 \pm 0.4\text{fT} \cdot \text{s/cm}$ which is significantly larger ($t_{RMS}(38) = 3$, $P_{RMS} = 0.005$) than the Germans' ($ISF_{RMS,German} = 2.1 \pm 0.3\,\text{fT} \cdot \text{s/cm}$).

For more details on the individual results of the integrated sustained fields, please refer to the appendix in Sec. B.1.

As mentioned in Sec. 3.3, the minimum of residual variance (RV_{min}) is a measure of the goodness of fit. The lower RV_{min}, the better the fit. The residual variance of the SF fit is $RV_{min,Chinese} = 0.33$ for the Chinese and $RV_{min,German} = 0.47$ for the German subjects, which shows that the Chinese' sustained fields were easier and better to be fitted than the Germans'.

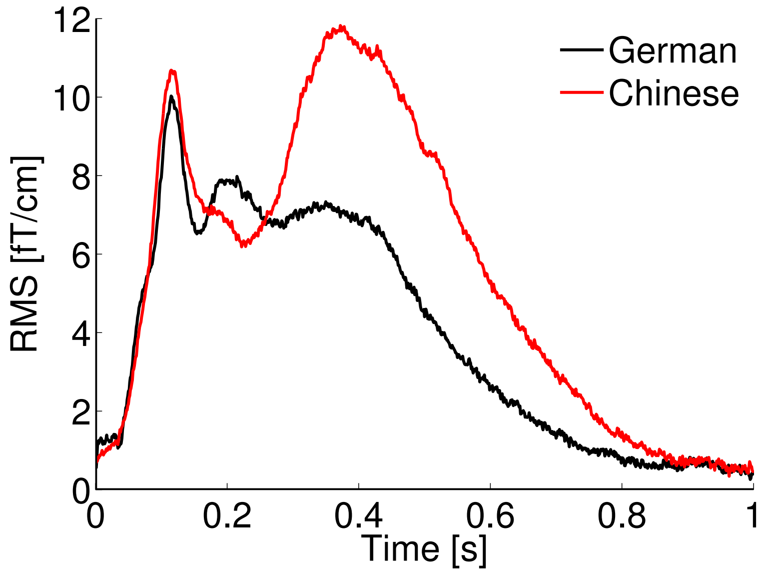


Figure 4.3: Root-mean-square of magnetogradiometers of Chinese and German subjects

Taking together all RMS for the linguistic stimuli, the Chinese subjects show an ISF of $ISF_{RMS,Chinese} = 3.6 \pm 0.4\,\mathrm{fT \cdot s/cm}$ which is about double the size of the German subjects' ISF ($ISF_{RMS,German} = 2.1 \pm 0.3\,\mathrm{fT \cdot s/cm}$). The results of the difference of RMS between both groups is also highly significant ($t(38)$=3, P=0.005) and thus fully confirms the results of the dipole model.

Since the language center (Wernicke-area) is known to be located in the left hemisphere, lateralization to the left hemisphere could be expected for neural activation. Our results, however, show no indication for lateralization in the Chinese group ($\Delta_{Ch}(ISF_{left}, ISF_{right}) = 0.5 \pm 0.7\,\mathrm{nAm \cdot s}$, $t_{Ch}(19) = 0.7$, $P_{Ch} = 0.49$), the excess in the right hemisphere of the German group is not statistically significant ($\Delta_{Ge}(ISF_{left}, ISF_{right}) = -1.1 \pm 0.7\mathrm{nAm \cdot s}$, $t_{Ge}(19) = 1.57$, $P_{Ge} = 0.13$), see Fig. 4.4 and Tab. 4.2.

	ISF_{RMS} [fT · s/cm]	
condition	**Chinese**	**German**
ling. stimuli	3.6 ± 0.4	2.1 ± 0.3
/ma1/	5.0 ± 0.7	2.7 ± 0.6
/ma2/	4.0 ± 0.5	2.3 ± 0.7
/ma3/	5.4 ± 0.5	2.7 ± 0.4
/ma4/	2.8 ± 0.5	1.6 ± 0.3
/mu1/	4.5 ± 0.4	2.5 ± 0.5
/mu2/	4.7 ± 0.5	2.5 ± 0.5
/mu3/	6.5 ± 0.7	3.0 ± 0.5
/mu4/	2.8 ± 0.4	2.0 ± 0.4
/o1/	1.9 ± 0.3	2.0 ± 0.3
/o2/	2.8 ± 0.5	1.8 ± 0.4
/o3/	3.5 ± 0.6	2.3 ± 0.5
/o4/	1.8 ± 0.4	1.1 ± 0.2
/ö1/	2.1 ± 0.5	1.3 ± 0.2
/ö2/	3.7 ± 0.6	2.0 ± 0.3
/ö3/	4.6 ± 0.6	2.2 ± 0.3
/ö4/	1.8 ± 0.4	1.4 ± 0.3

Table 4.1: Integrated sustained fields of the root-mean-square of all gradiometers

The results of the model-independent RMS of all gradiometers confirms the result of the dipole model. The Chinese group consistently shows larger integrated sustained fields than the German group. Only the ISF_{RMS} of vowel /o1/ is approximately equal for both groups.

	ISF [nAm · s]	
condition	**Chinese**	**German**
binaural	-9.1 ± 1.0	-4.1 ± 1.3
left hemisphere	-8.8 ± 1.1	-4.6 ± 1.3
right hemisphere	-9.4 ± 1.1	-3.5 ± 1.3
Δ(left,right)	0.5 ± 0.7	-1.1 ± 0.7

Table 4.2: Integrated sustained field of both hemispheres

There is no statistically significant lateralization effect in neither the Chinese nor the German group ($t_{Ch}(19) = 0.7$, $P_{Ch} = 0.49$, $t_{Ge}(19) = 1.57$, $P_{Ge} = 0.13$).

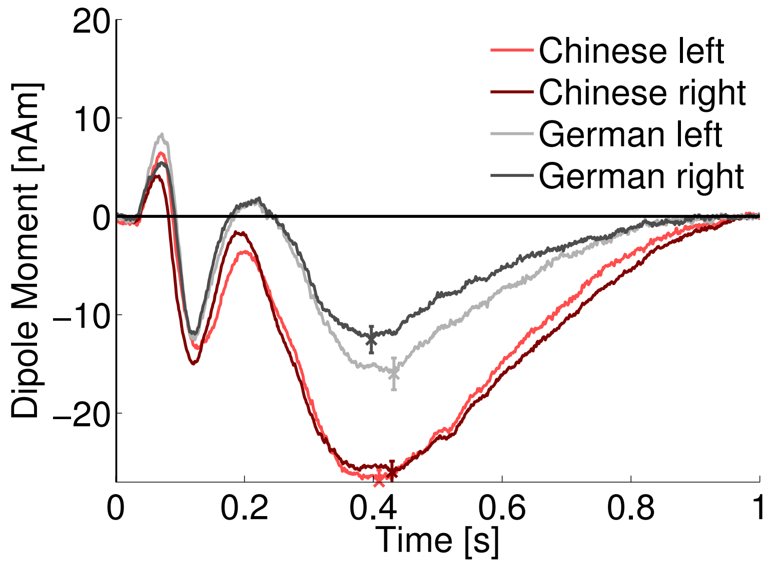
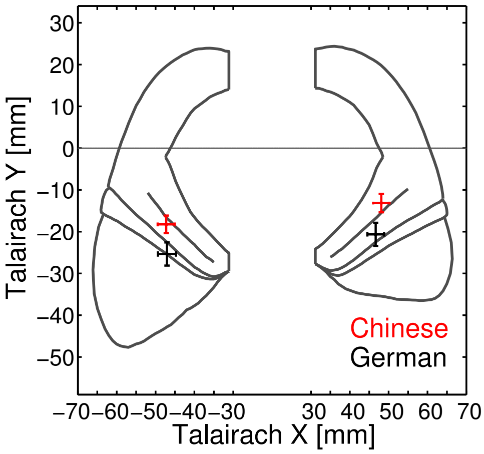


Figure 4.4: No lateralization effect

No indication for lateralization in the Chinese group was found ($\Delta_{Ch}(ISF_{left}, ISF_{right}) = 0.5 \pm 0.7$ nAm · s, $t_{Ch}(19) = 0.7$, $P_{Ch} = 0.49$). The excess in the right hemisphere of the German group is not statistically significant ($\Delta_{Ge}(ISF_{left}, ISF_{right}) = -1.1 \pm 0.7$nAm · s, $t_{Ge}(19) = 1.57$, $P_{Ge} = 0.13$). The error bars within the graphs were obtained from the standard error of mean of the sustained field peaks.

Comparing the dipole localizations of the German and Chinese subjects reveal a significant group-specific difference in the y-direction ($t_y(38) = 4.1$, $P_y = 0.0002$). The Chinese subjects' dipoles are located 7.3 ± 2.0 mm anterior to the German dipoles, while no significant differences in the x- and z-direction ($\Delta x = 0.8 \pm 1.2$ mm, $\Delta z = 2.5 \pm 1.2$ mm) were found ($t_x(38) = 0.74$, $P_x = 0.46$, $t_z(38) = 1.80$, $P_z = 0.08$).

Since we used a spherical head model in our data analysis instead of the actual heads from MRI, we need to be careful not to draw any early conclusions. But it is certainly a good start to further investigate this aspect by segmenting the individual Heschl's gyri.



Talairach coordinates [mm]

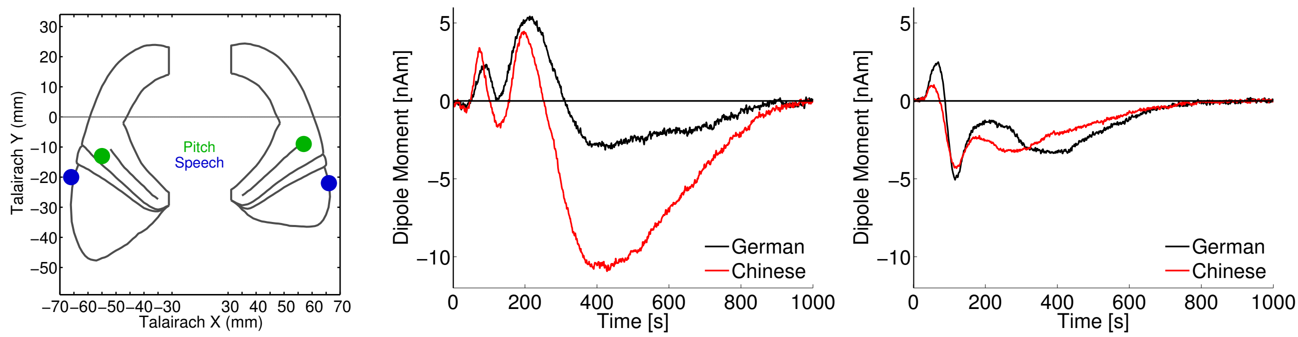
left	**x**	**y**	**z**
Chinese	-47.3 ± 1.0	-18.3 ± 1.7	2.6 ± 1.4
German	-47.1 ± 1.1	-25.3 ± 1.4	-0.6 ± 1.5
right	**x**	**y**	**z**
Chinese	$+48.1 \pm 1.2$	-13.2 ± 1.5	3.3 ± 1.0
German	$+46.7 \pm 1.3$	-20.7 ± 1.6	1.6 ± 1.0

Figure 4.5: Localization of dipoles for linguistic stimuli

In this projection of the localization of the dipoles onto the x-y plane one can see the difference between German and Chinese subjects in the anterior-posterior direction ($\Delta y = 7.3 \pm 2.0$ mm, $t_y(38) = 3.6$, $P_y = 0.0008$). No significant differences in the x- and z-direction ($\Delta x = 0.8 \pm 1.2$ mm, $\Delta z = 2.5 \pm 1.2$ mm) were found ($t_x(38) = 0.74$, $P_x = 0.46$, $t_z(38) = 1.80$, $P_z = 0.08$).

4-Dipole Model As mentioned earlier in Sec. 3.3, I applied a 4-dipole model to the measured data in order to evaluate the neural activation in the bilateral region in lateral Heschl's gyrus, which are known for their high activation to pitch paradigms (Patterson et al., 2002), and in the superior temporal sulcus that are known for their high activation to vowel to non-speech contrasts (Kaas et al., 1999; Uppenkamp et al., 2006).

The projection of the localization of the 4-dipole model onto the x-y plane are included in Fig. 4.6(a). For the exact Talairach coordinates, please refer to Fig. 3.12. Fig. 4.6 shows



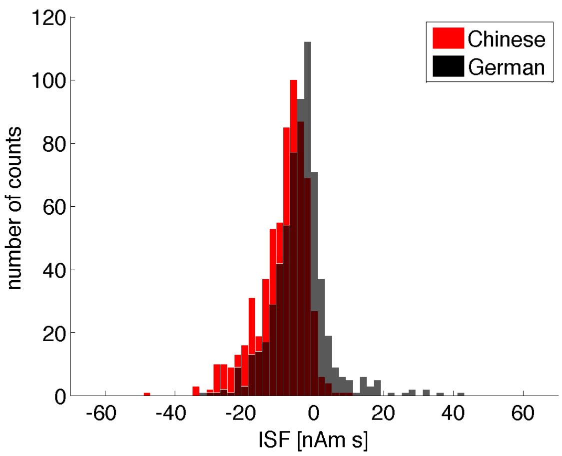
(a) **Localization** (b) **Pitch center** (c) **Speech center**

Figure 4.6: 4-Dipole Model

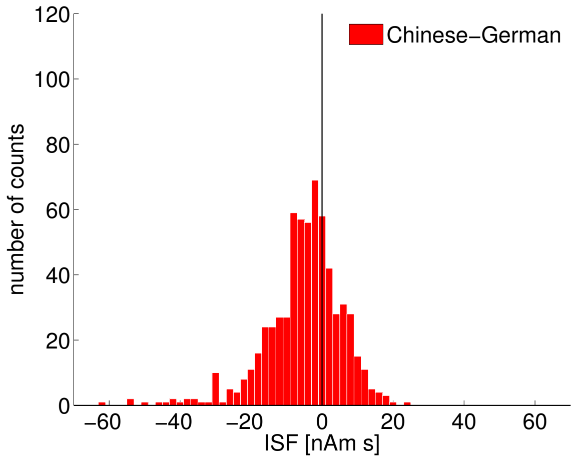
In (a) the localization of the four dipoles on the pitch and speech center is displayed. There is a lot of activation in the pitch center (b), while there is only little activation to be seen at the speech center (c). The sustained field of the Chinese is significantly larger than the size of the Germans' at the pitch center ($ISF_{Ch,pitch} = 3.8 \pm 0.9$ nAm $\cdot$ s, $ISF_{Ge,pitch} = 0.7 \pm 0.8$ nAm $\cdot$ s, $t(38) = 2.57$, $P = 0.014$), while at the speech center Chinese and Germans have about the same integrated sustained fields ($ISF_{Ch,speech} = 0.9 \pm 0.4$ nAm $\cdot$ s, $ISF_{Ge,speech} = 1.0 \pm 0.5$ nAm $\cdot$ s, $t(38) = 0.16$, $P = 0.877$).

the dipole waveforms fitted on the sustained field at the pitch (b) and speech center (c). From Fig. 4.6 one can easily see that there is a lot of activation in the pitch center, while there is only little activation to be seen at the speech center. Furthermore, the sustained field of the Chinese is significantly larger than the size of the Germans' at the pitch center ($ISF_{Ch,pitch} = 3.8 \pm 0.9$ nAm $\cdot$ s, $ISF_{Ge,pitch} = 0.7 \pm 0.8$ nAm $\cdot$ s, $t_{Pitch}(38) = 2.57$, $P_{Pitch} = 0.014$), while the waveforms at the speech center show a slightly different temporal behavior. Taking only a look at the integrated sustained field at the speech center, Chinese and Germans have about the same size ($ISF_{Ch,speech} = 0.9 \pm 0.4$ nAm $\cdot$ s, $ISF_{Ge,speech} = 1.0 \pm 0.5$ nAm $\cdot$ s). There is no significant difference between their ISF ($t_{speech}(38) = 0.16$, $P_{speech} = 0.877$).

Distribution of Integrated Sustained Field With the clear results from the dipole model, which were confirmed by the model-independent RMS, it is tempting to assume that one can distinguish Chinese from German speakers by the size of the sustained field. This, however, is not the case. Looking at the actual distribution of integrated sustained fields among both groups shows the difficulty of this. In Fig. 4.7, all single results of each hemisphere, stimulus and tone are displayed in the distribution. In fact, there is a considerable overlap between German and Chinese distributions (a), which is clarified even more in the distribution of differences between the groups (b).



(a) ISF Distribution for Chinese and Germans



(b) Distribution of difference between groups

Figure 4.7: Distribution of integrated sustained field

(a) In this histogram, all single results of each hemisphere, stimulus and tone are displayed. The Chinese and the German subjects show a big overlap between their distributions, which do not differ much in their form.

(b) The histogram displays the difference between both groups. It is shifted to the negative direction which reflects that the Chinese group has larger integrated sustained fields than the Germans.

Duration Dependence From Fig. 4.1 a notable difference in the size of the signal for different stimuli can be noticed. Syllables have larger sustained fields than vowels, which is also the case within one category. Tone 3 with the longest natural duration has the largest sustained field, Tone 4 with the shortest natural duration has the smallest sustained field, also see Sec. 3.1. It turns out that there is a strong correlation between integrated sustained fields and duration of stimuli, namely $\rho = 0.91$ for the Chinese and $\rho = 0.72$ for the German group (Pearson's coefficient). Comparing linear regressions of the datasets shows that the Chinese ($m_{Chinese} =$

$-36.2 \cdot (t - 0.11)$ nAm) have twice the slope of the German subjects ($m_{German} = -18.3 \cdot (t - 0.15)$ nAm), see Fig. 4.8.

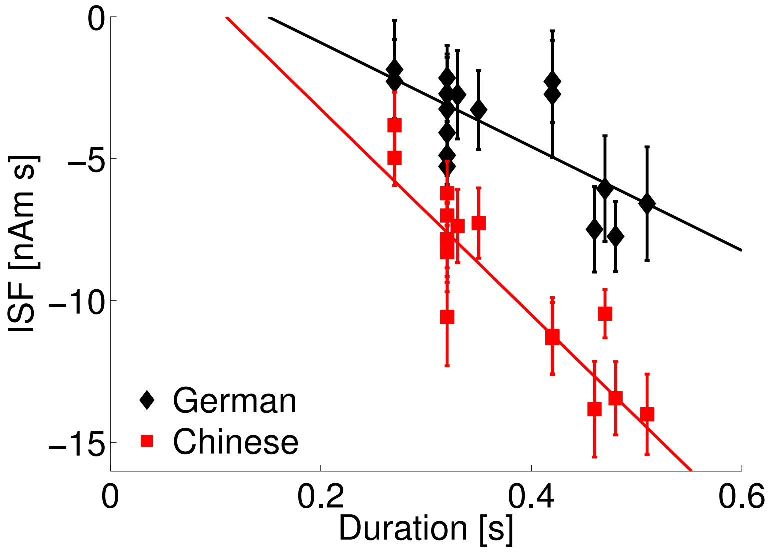
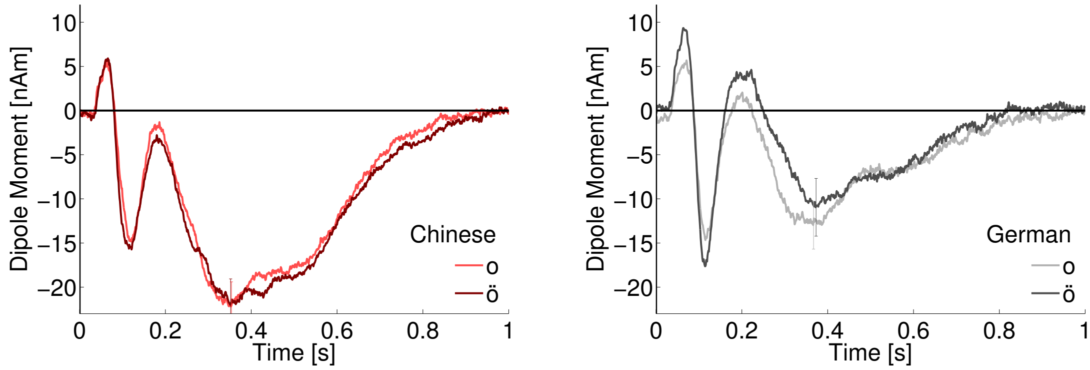


Figure 4.8: Duration dependence

There is a strong correlation between the ISF and the duration of stimuli. Linear regressions on our dataset showed for the Chinese ($m_{Chinese} = -36.2 \cdot (t - 0.11)$ nAm) to have twice the slope of the German subjects ($m_{German} = -18.3 \cdot (t - 0.15)$ nAm).

Phonetic Effects The vowels /o/ and /ö/ are both part of the German phonetic system, while /ö/ does not occur in Chinese. As expected, the sustained field evoked by the vowel /o/ did not show any difference to the sustained field evoked by the vowel /ö/ in the German group ($\Delta_{Ge}(ISF_{/o/} - ISF_{/ö/}) = -0.7 \pm 0.6$ nAm · s, $t_{Ge}(19) = 1.17$, $P_{Ge} = 0.26$).

Unlike the mismatch negativity (MMN) studies, see Sec.2.4, that have found differences between sounds that occur in subjects' mother tongue and those that do not as mentioned earlier in Sec. 2.4, we actually did not find any significant differences in the sustained field evoked by the vowels /o/ and /ö/ for the Chinese group ($\Delta_{Ch}(ISF_{/o/} - ISF_{/ö/}) = 0.5 \pm 0.5$ nAm · s, $t_{Ch}(19) = -1$, $P_{Ch} = 0.33$), see Fig. 4.9 and Tab. 4.3. Taking a deeper look at the localizations of dipoles from the other MMN studies, we think it might be due to different generators to have such opposite results. This will be further discussed in Sec. 5.



(a) Chinese **(b)** German

Figure 4.9: Phonetic effects

The vowels /o/ and /ö/ are both part of the German phonetic system, while /ö/ does not occur in Chinese. Both vowels do not show any differences of integrated sustained fields in neither the German ($\Delta_{Ge}(ISF_{/o/} - ISF_{/ö/}) = -0.7 \pm 0.6$ nAm·s, $t_{Ge}(19) = 1.17$, $P_{Ge} = 0.26$) nor the Chinese group ($\Delta_{Ch}(ISF_{/o/} - ISF_{/ö/}) = 0.5 \pm 0.5$ nAm·s, $t_{Ch}(19) = -1$, $P_{Ch} = 0.33$).
The error bars within the graphs were obtained from the standard error of mean of the sustained field peaks.

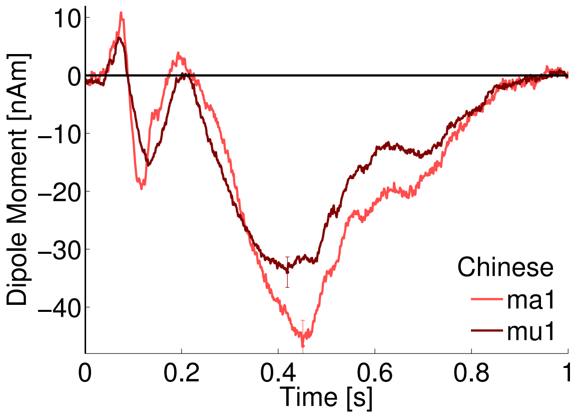
	ISF [nAm·s]	
condition	**Chinese**	**German**
/o/	-6.8 ± 1.1	-3.6 ± 1.1
/ö/	-7.3 ± 1.1	-3.0 ± 1.4
Δ(o - ö)	0.5 ± 0.5	-0.7 ± 0.6
$t(19)$	-1	1.17
P	0.33	0.26

Table 4.3: Phonetic effects

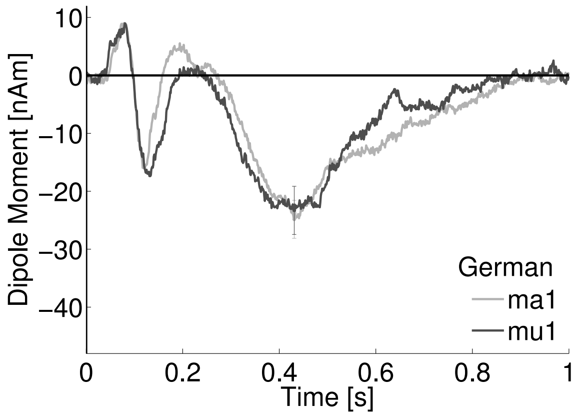
The vowels /o/ and /ö/ do not show any differences of integrated sustained fields in neither the German nor the Chinese group.

Semantic effects We included the phonological minimal pair of the meaningful /ma1/ and the meaningless syllable /mu1/ in our paradigm. In Fig. 4.10 one can see the dipole waveforms for the syllables /ma1/ and /mu1/ for the Chinese and the German group.

As expected, no difference between these syllables could be found in the German group who also did not perceive any meaning ($t_{Ge}(19) = 0.89$, $P_{Ge} = 0.38$). The Chinese group, however, displayed a significant difference between the meaningful /ma1/ and meaningless /mu1/, see Fig. 4.10 and Tab. 4.4. In the Chinese group the sustained field evoked by the meaningful syllable /ma1/ is significantly larger than that of the meaningless syllable /mu1/ ($t_{Ch}(19) = 3.33$, $P_{Ch} = 0.004$).



(a) **Chinese**



(b) **German**

Figure 4.10: Semantic effects

As expected, no difference between the syllables /ma1/ and /mu1/ could be found in the German group who did not perceive any meaning. The Chinese group, however, displayed a significant difference between the meaningful /ma1/ and meaningless /mu1/, while no differences were found for the other matching pairs of tones.

The error bars within the graphs were obtained from the standard error of mean of the sustained field peaks.

We further evaluated the asymmetry between the responses to /ma1/ and /mu1/ of the Chinese group by integrating over 100 ms intervals to investigate the temporal development of the asymmetry, see Fig. 4.11. The figure shows that the asymmetry $\frac{/\mathrm{ma1}/ - /\mathrm{mu1}/}{/\mathrm{ma1}/ + /\mathrm{mu1}/}$ starts at about 400 ms after tone onset. The asymmetry is especially marked in the time interval from 400 to 800 ms after stimulus onset, where it reaches the value 0.146 ± 0.037 ($t_{Ch}(19) = 3.95$, $P_{Ch} = 0.0009$). As expected, there is no significant asymmetry in the German group.

No other differences of sustained field were found for the other matching pairs of tones 2-4 of the syllables /ma/ and /mu/, which were all meaningful. For the exact numbers of the particular integrated sustained fields and their differences, see Tab. 4.4.

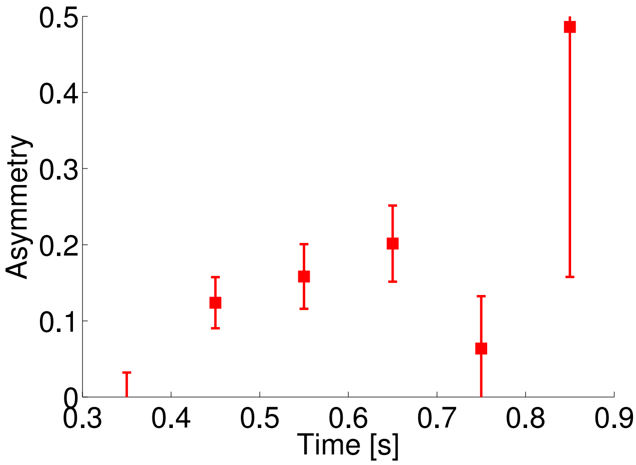


Figure 4.11: $\frac{/\mathrm{ma1}/ - /\mathrm{mu1}/}{/\mathrm{ma1}/ + /\mathrm{mu1}/}$ - Asymmetry
The asymmetry between the responses to /ma1/ and /mu1/ of the Chinese group was integrated over 100 ms intervals to investigate the temporal development of the asymmetry. The figure shows that the asymmetry $\frac{/\mathrm{ma1}/ - /\mathrm{mu1}/}{/\mathrm{ma1}/ + /\mathrm{mu1}/}$ starts at about 400 ms after tone onset. The asymmetry is especially marked in the time interval from 400 to 800 ms after stimulus onset, where it reaches the value 0.146 ± 0.037 ($t_{Ch}(19) = 3.95$, $P_{Ch} = 0.0009$). As expected, there is no significant asymmetry in the German group.

This is in line with the observation that, apart from the large difference in size, there is also a significant difference in the waveform of the sustained field between both groups. The sustained field of Chinese speakers falls off more slowly compared to that of the German group. In order to quantify this effect we normalized the response curves to syllables to -1 in their minimum, see Fig. 4.12. After normalization it can clearly be seen that the signals of Chinese listeners exhibit a slower decay. The difference between the normalized waveforms, integrated from 400 to 1000 ms after stimulus onset, is -0.062 ± 0.024 s ($t_{syl}(38) = -2.56$, $P_{syl} = 0.01$).

For the vowels we also observed an excess, it failed, however, to reach significance ($-0.045 \pm$

ISF [nAm·s]						
	Chinese			German		
	/ma/	/mu/	Δ(ma - mu)	/ma/	/mu/	Δ(ma - mu)
Tone 1	-13.4 ± 1.0	-10.5 ± 0.7	-3.0 ± 0.9	-6.8 ± 1.1	-6.1 ± 1.5	-0.7 ± 0.9
Tone 2	-11.2 ± 1.4	-11.3 ± 1.3	0.1 ± 1.2	-2.3 ± 1.4	-2.7 ± 2.2	0.4 ± 1.8
Tone 3	-14.0 ± 1.4	-13.8 ± 1.7	-0.2 ± 1.3	-6.6 ± 2.0	-7.5 ± 1.5	0.9 ± 1.6
Tone 4	-7.4 ± 1.3	-7.3 ± 1.2	-0.1 ± 0.8	-2.7 ± 7.0	-3.3 ± 1.4	0.5 ± 0.9

Table 4.4: Semantic effects

The German group did not show any differences in the integrated sustained fields between the various matching pairs (ma-mu) of the tones 1-4, while the Chinese group only displayed a significant difference between the meaningful /ma1/ and meaningless /mu1/; no differences were found for the other matching pairs of the tones 2-4.

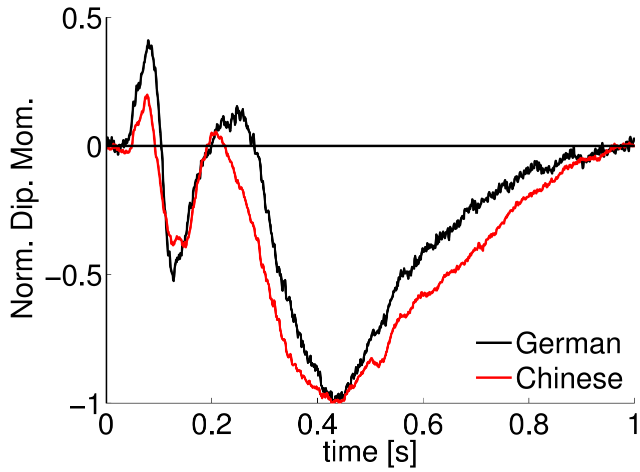


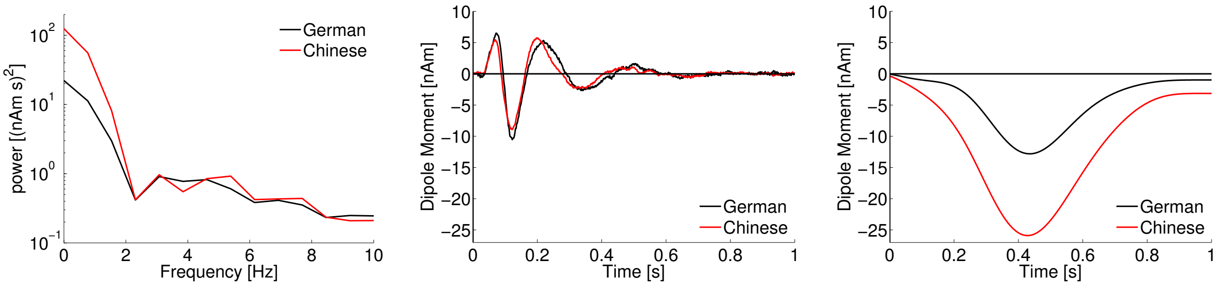
Figure 4.12: Normalized waveforms

The sustained field of Chinese speakers falls off more slowly compared to that of the German group. The difference between the normalized waveforms, integrated from 400 to 1000 ms after stimulus onset, is -0.062 ± 0.024 s ($t_{syl}(38) = -2.56$, $P_{syl} = 0.01$).

$0.05s$, $t_{vow}(38) = -0.9$, $P_{vow} = 0.37$). Due to the prominent transients overlapping with the onset of the SF, we could not derive a comparable measure for that onset.

Effect of Filtering Looking at the power spectrum of our data, it can be noted that the difference between German and Chinese data is only visible below 2.3 Hz which is also the bandwidth of sustained responses. For transient signals (power spectrum above 2.3 Hz) no differences are expected.

The usage of high- and low-pass-filter at 2.3 Hz confirms this view on the power spectrum. By applying a high-pass-filter (butter worth filter of forth order, $f_{Nyquist} = 1000/2\text{Hz}$) at 2.3Hz, the sustained field almost completely vanishes, leaving approximately the same dipole waveforms for Chinese and German subjects. Only transient components remain. Applying a low-pass-filter at 2.3 Hz, however, leaves only the sustained field, removing all transient components.



(a) Power spectrum **(b) High-pass-filter at 2.3 Hz** **(c) Low-pass-filter at 2.3 Hz**

Figure 4.13: Effect of filtering

(a) In this power spectrum, the difference between German and Chinese data is strong for frequencies below 2.3 Hz, while below 2.3 Hz none are expected.

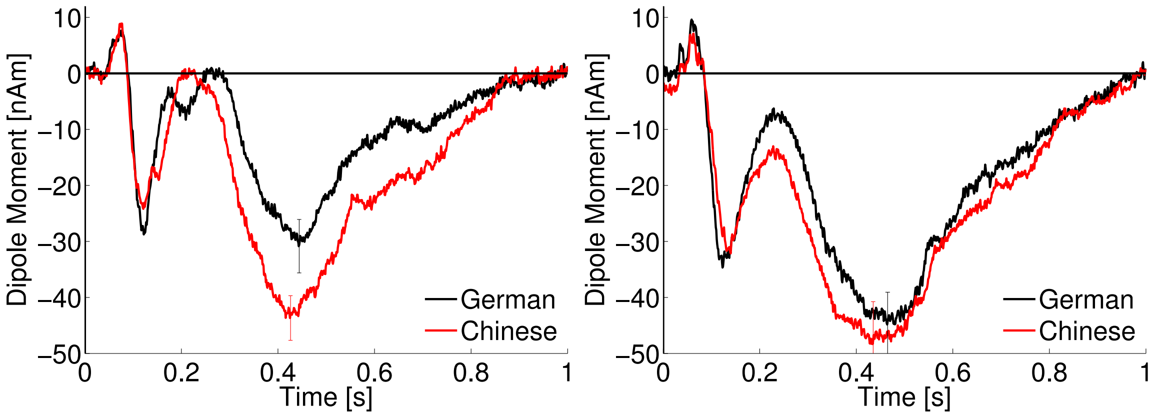
(b) Applying a high-pass-filter at 2.3 Hz makes the difference between German and Chinese data vanish. Only transient components are visible, although they do not show any differences.

(c) Applying a low-pass-filter at 2.3 Hz leaves only the sustained field, removing all transient components.

4.1.2. Linguistic vs. Musical Stimuli

In a separate experiment the spoken syllable /ma1/ and a tone of a French horn (b-flat, $f_0 = 117$ Hz) were randomly presented to a sub-sample of 11 Chinese and 14 Germans. In Fig.

4.14 the dipole waveforms of the mentioned stimuli are displayed comparing the Chinese and German sub-sample. As in the earlier experiment regarding all 8 syllable stimuli which were presented in random order, for signals evoked by the spoken syllable /ma1/ there was also a highly significant group specific difference ($t_{ma1}(23) = 3.2$, $P_{ma1} = 0.004$) in this experiment. In contradistinction to the speech stimuli, there was no significant group specific difference for the signals evoked by the horn tone ($t_{horn}(23) = 0.88$, $P_{horn} = 0.39$), see Tab. 4.5.



(a) Linguistic stimulus: /ma1/ **(b) Musical stimulus: French horn**

Figure 4.14: Linguistic vs musical stimuli

The spoken syllable /ma1/ and a tone of a French horn (b-flat, $f_0 = 117$ Hz) were randomly presented to a sub-sample of 11 Chinese and 14 Germans. For signals evoked by the spoken syllable /ma1/ there was also a highly significant group specific difference ($t_{ma1}(23) = 3.2$, $P_{ma1} = 0.004$) in this second experiment. In contradistinction to the speech stimuli, there was no significant group specific difference for the signals evoked by the horn tone ($t_{horn}(23) = 0.88$, $P_{horn} = 0.39$).

The error bars within the graphs were obtained from the standard error of mean of the sustained field peaks.

It was comforting to see that the integrated sustained fields did not depend on the environment in which the stimuli were presented. In Tab. 4.6 and Fig. 4.15 only those subjects who participated in both experiments were taken under consideration. The integrated sustained fields for the syllable /ma1/ obtained in the experiment, where only this syllable and the horn tone were presented, were for both groups fully consistent with those of the first experiment,

	ISF [nAm · s]		
condition	**Chinese**	**German**	**Δ(Ch, Ge)**
/ma1/	-13.3 ± 1.1	-8.1 ± 1.2	5.3 ± 1.6
horn	-17.3 ± 1.8	-15.0 ± 1.6	2.3 ± 2.4
Δ(ma1, horn)	4.0 ± 2.1	6.9 ± 1.3	

Table 4.5: Linguistic vs musical stimuli

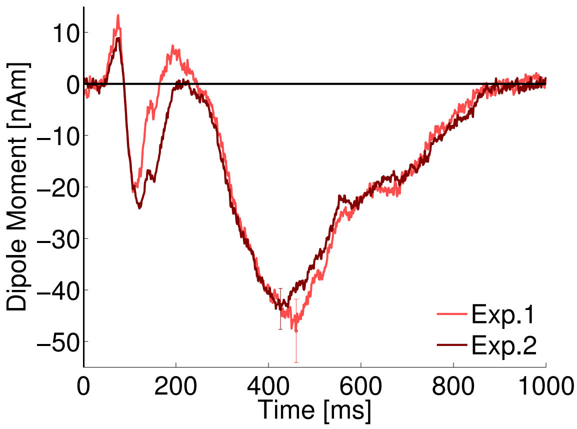
There was a highly significant group specific difference for the integrated sustained fields to the spoken syllable /ma1/ ($t_{ma1}(23) = 3.2$, $P_{ma1} = 0.004$) in the second experiment of 11 Chinese and 14 German subjects. In contradistinction to this, there was no significant group specific difference for the signals evoked by the horn tone ($t_{horn}(23) = 0.88$, $P_{horn} = 0.39$).

where all 8 syllable stimuli were presented in random order. Fig. 4.15 clearly demonstrates the similarities of responses to /ma1/ of the first and second experiment for the Chinese group as the waveforms from both experiments clearly overlap ($t_{Ch}(10) = 0.15$). The dipole waveforms of the German group, however, suggest differences between both experiments but it is statistically insignificant ($P_{Ch} = 0.88$; $t_{Ge}(13) = 0.19$, $P_{Ge} = 0.85$).

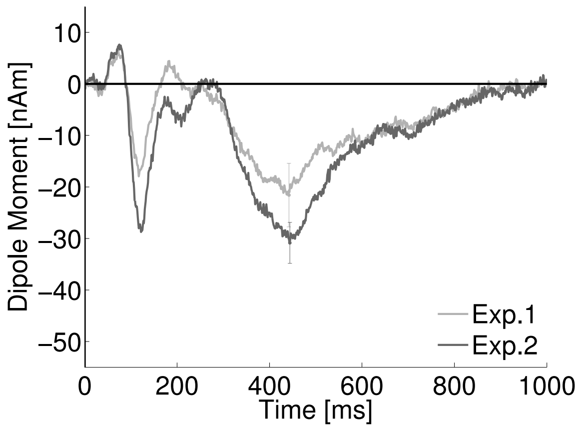
	ISF [nAm · s]	
/ma1/ from	**Chinese**	**German**
Exp 1	13.5 ± 1.3	7.7 ± 1.4
Exp 2	13.3 ± 1.1	8.1 ± 1.2
Δ(Exp 1, Exp 2)	0.2 ± 1.9	-0.3 ± 1.3

Table 4.6: Comparison of integrated sustained fields of /ma1/

The integrated sustained fields did not depend on the environment in which the stimuli were presented. The ISF for the syllable /ma1/ from the first experiment are for both groups fully consistent to those from the second experiment.



(a) Chinese



(b) German

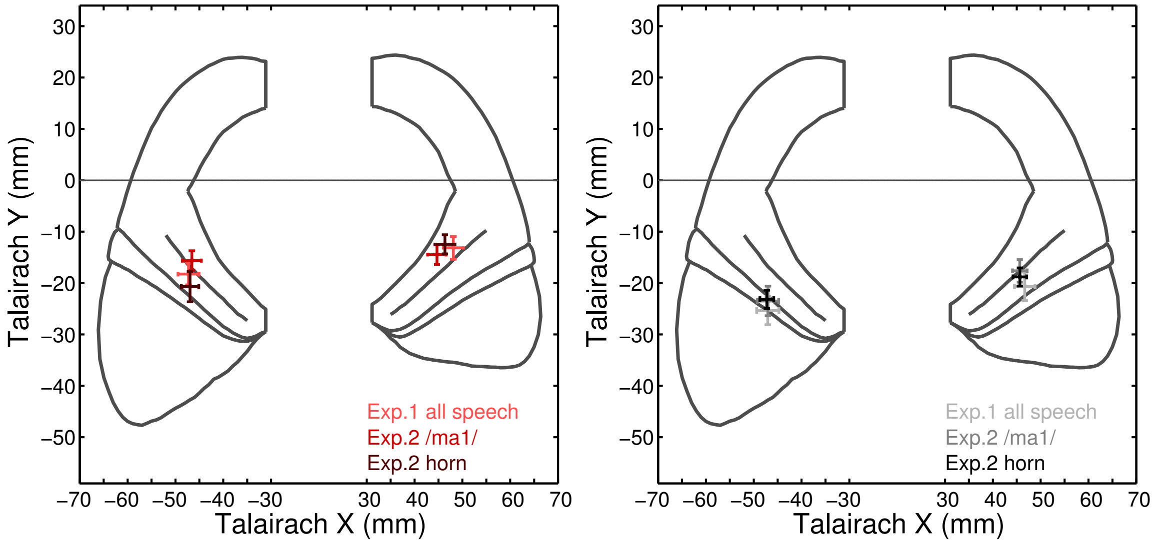
Figure 4.15: Comparison of sustained fields of /ma1/ from both experiments

The dipole waveforms of this figure are the averages over those subjects who participated in both experiments: 11 Chinese and 14 German subjects. In the first experiment /ma1/ was one of eight syllable stimuli which were presented in random order, while in the other experiment only this syllable and the horn tone were presented.

This figure demonstrates it very clearly for the Chinese group as the waveforms from both experiments clearly overlap ($t_{Ch}(10) = 0.15$,$P_{Ch} = 0.88$). Although the graph suggests differences between the first and second experiment for the German group, statistics does not confirm it ($t_{Ge}(13) = 0.19$, $P_{Ge} = 0.85$).

The error bars within the graphs were obtained from the standard error of mean of the sustained field peaks.

As expected, the generators of the linguistic stimulus /ma1/ from the second experiment agree well with the generators of the linguistic stimuli from the first experiment for both groups. Furthermore, the generators to the musical stimulus also agree well with them, see Fig. 4.16.



(a) Chinese **(b) German**

Figure 4.16: Comparison of dipole localizations
The generators of the linguistic stimulus /ma1/ from the second experiment agree well with the generators of the linguistic stimuli from the first experiment. Furthermore, the generators to the musical stimulus also agree well with them. This could be shown for both groups.

4.2. Components

In Fig. 4.17 a composition of different dipole waveforms is displayed. For each group, the waveforms were averaged over the linguistic stimuli from Sec. 3.1 and fitted on various components (P1, N1, P2, SF). Thus, the curves from Fig. 4.17 show four different waveforms per group, one in each partition, which are therefore not smooth. The error bars were obtained from the standard error of mean of each component's peak.

The average values of the components are presented in Tab. 4.7 for both groups. They offer a mixed picture about the relationship between German and Chinese subjects for each component. As already seen at the integrated sustained field in Sec. 4.1.1, the Chinese have a significantly

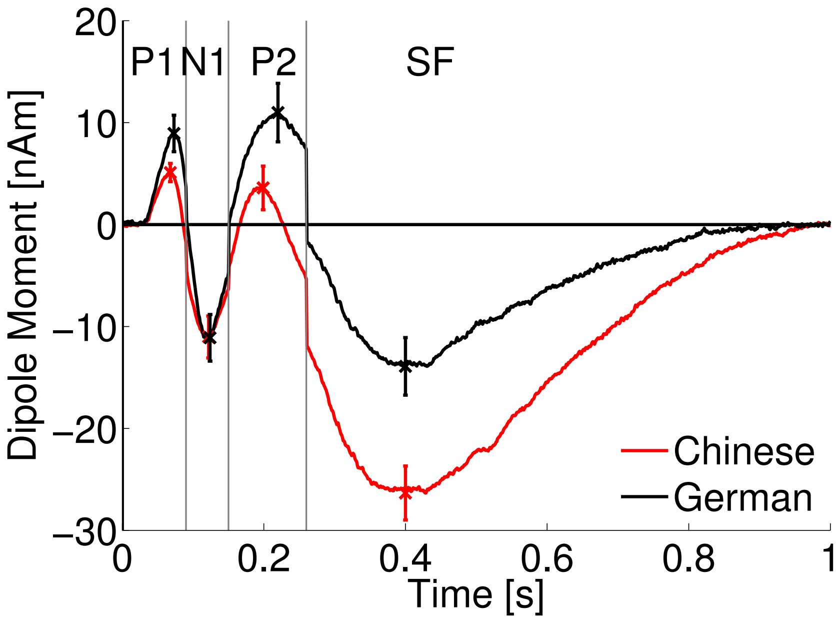


Figure 4.17: Composition of dipole waveforms for each component

Each partition of this composition of four different dipole waveforms is a result of another pair of freely fitted effective dipoles on the respective component (P1, N1, P2, SF).

The error bars within the graphs were obtained from the standard error of mean of the peaks of each component.

Peaks [nAm]

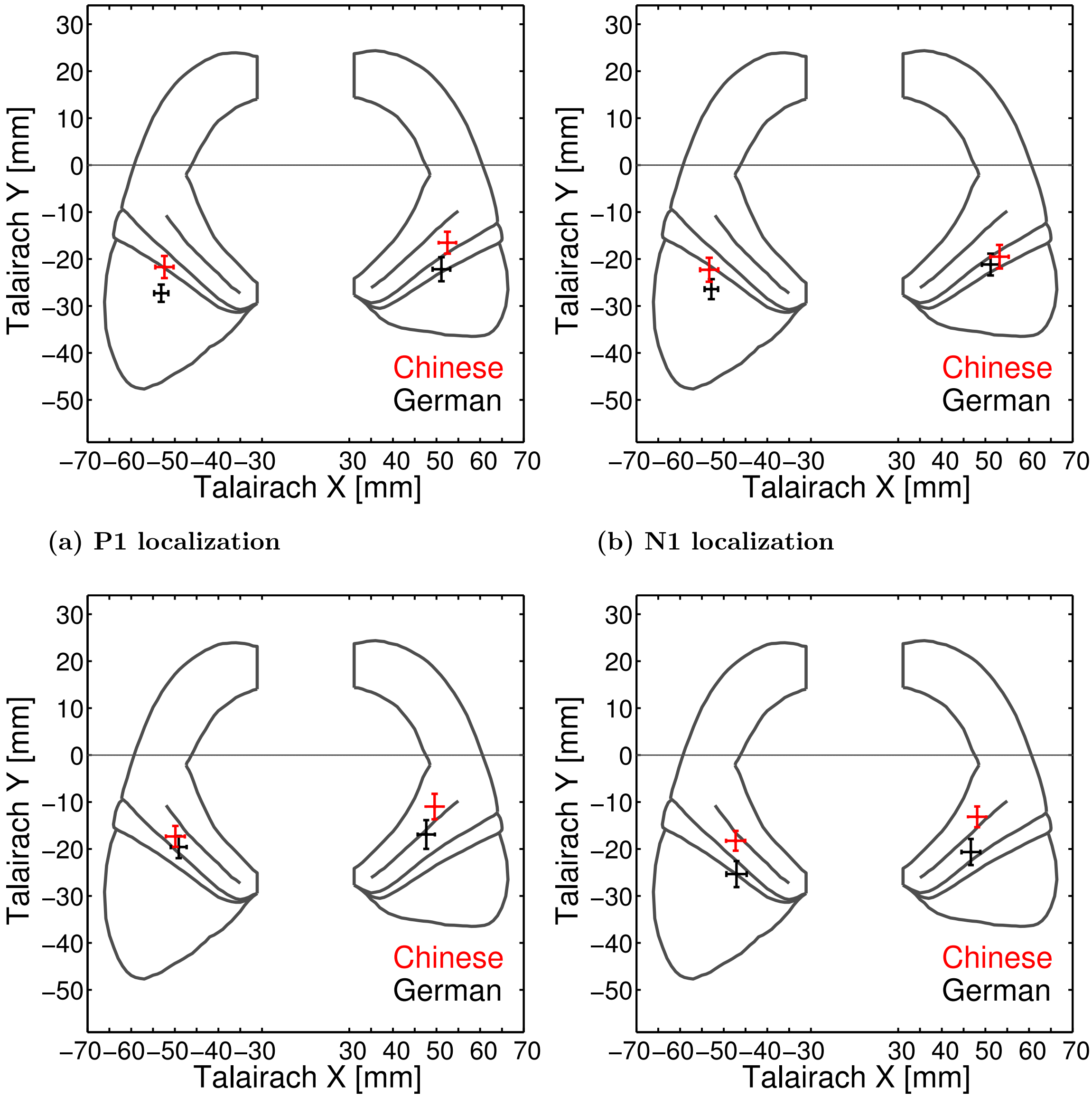
component	Chinese	German
P1	11.60 ± 0.90	16.18 ± 1.79
N1	-18.49 ± 2.06	-20.55 ± 2.28
P2	10.02 ± 2.14	21.27 ± 2.87
SF	-36.14 ± 2.65	-27.34 ± 2.82

Table 4.7: Components of dipole waveforms of linguistic stimuli

The P1 and P2 component of the German group is significantly larger than the Chinese' ($t_{P1}(38) = 2.29$, $P_{P1} = 0.03$, $t_{P2}(38) = 3.14$, $P = 0.003$), while there is no significant difference between the two groups for the N1 component ($t_{N1}(38) = 0.67$, $P = 0.51$). Finally, the SF component is significantly larger for Chinese than for Germans ($t_{SF}(38) = 2.27$, $P = 0.03$).

larger sustained field than the Germans ($t_{SF}(38) = 2.27$, $P_{SF} = 0.03$). The N1 component, however, does not show any significant differences between the groups ($t_{N1}(38) = 0.67$, $P_{N1} = 0.51$), while the P1 and P2 components of the German group are significantly larger than the Chinese' ($t_{P1}(38) = 2.29$, $P_{P1} = 0.03$, $t_{P2}(38) = 3.14$, $P_{P2} = 0.003$).

Taking a look at the localization of dipoles for every component, we find the Chinese localization of dipole always to be anterior to the German's. This difference in y-direction is significant for the P1, P2 and SF component, while there is no significant difference in x-direction among any component. The difference between Germans and Chinese in z-direction is significant for the P1 and N1 components, while it is not for the P2 and SF components, see Fig. 4.18. The exact dipole localizations, as well as the differences between the generators of the German and Chinese group for each component, and their $t(38)$ and P values from the unpaired two-tailed Student's t-test are presented in Tab. 4.8. Statistical methods were described in Sec. 3.3.



(a) **P1 localization**

(b) **N1 localization**

(c) **P2 localization**

(d) **SF localization**

Figure 4.18: Dipole localization of components

Applying a 2-dipole model with a freely fitted dipole in each hemisphere leads to the following dipole localizations of the fitted components P1, N1, P2, SF. In x-direction, there is no significant difference between the Chinese and Germans among all components. As can be seen in this figure, the Chinese' dipole localization are always anterior to the Germans'. This difference in y-direction is significant for the P1, P2 and SF components.

	left hemisphere			right hemisphere		
	x [mm]	**y [mm]**	**z [mm]**	**x [mm]**	**y [mm]**	**z [mm]**
Chinese	-52.4 ± 2.1	-21.7 ± 2.3	6.4 ± 2.2	52.5 ± 2.0	-16.5 ± 2.3	6.1 ± 2.1
German	-53.1 ± 1.6	-27.3 ± 1.8	1.5 ± 2.2	51.1 ± 2.0	-22.2 ± 2.6	4.0 ± 2.0

(a) P1 localization

	left hemisphere			right hemisphere		
	x [mm]	**y [mm]**	**z [mm]**	**x [mm]**	**y [mm]**	**z [mm]**
Chinese	-53.3 ± 2.1	-22.3 ± 2.6	6.6 ± 2.0	53.2 ± 2.1	-19.5 ± 2.5	7.2 ± 1.9
German	-52.8 ± 1.5	-26.4 ± 2.1	2.6 ± 2.1	51.2 ± 2.0	-21.2 ± 2.3	2.3 ± 1.9

(b) N1 localization

	left hemisphere			right hemisphere		
	x [mm]	**y [mm]**	**z [mm]**	**x [mm]**	**y [mm]**	**z [mm]**
Chinese	-49.9 ± 2.2	-17.3 ± 2.2	3.4 ± 2.4	49.6 ± 2.1	-11.0 ± 2.7	3.2 ± 2.1
German	-49.1 ± 1.8	-19.6 ± 2.4	-0.6 ± 2.5	47.6 ± 2.0	-16.9 ± 3.1	1.9 ± 2.3

(c) P2 localization

	left hemisphere			right hemisphere		
	x [mm]	**y [mm]**	**z [mm]**	**x [mm]**	**y [mm]**	**z [mm]**
Chinese	-47.3 ± 1.0	-18.3 ± 1.7	2.6 ± 1.4	$+48.1 \pm 1.2$	-13.2 ± 1.5	3.3 ± 1.0
German	-47.1 ± 1.1	-25.3 ± 1.4	-0.6 ± 1.5	$+46.7 \pm 1.3$	-20.7 ± 1.6	1.6 ± 1.0

(d) SF localization

component	Δx [mm]	$t(38)$	P	Δy [mm]	$t(38)$	P	Δz [mm]	$t(38)$	P
P1	0.3 ± 1.1	0.34	0.74	5.6 ± 1.8	3.25	0.0024	3.5 ± 1.4	2.3	0.03
N1	1.3 ± 1.2	1.21	0.24	2.9 ± 1.9	1.56	0.13	4.4 ± 1.6	2.9	0.006
P2	1.3 ± 0.9	1.41	0.17	4.1 ± 1.8	2.13	0.04	2.7 ± 1.7	1.52	0.136
SF	0.8 ± 1.2	0.74	0.46	7.3 ± 2.0	3.6	0.0008	2.5 ± 1.2	1.80	0.08

(e) Differences between Chinese and German dipole localization

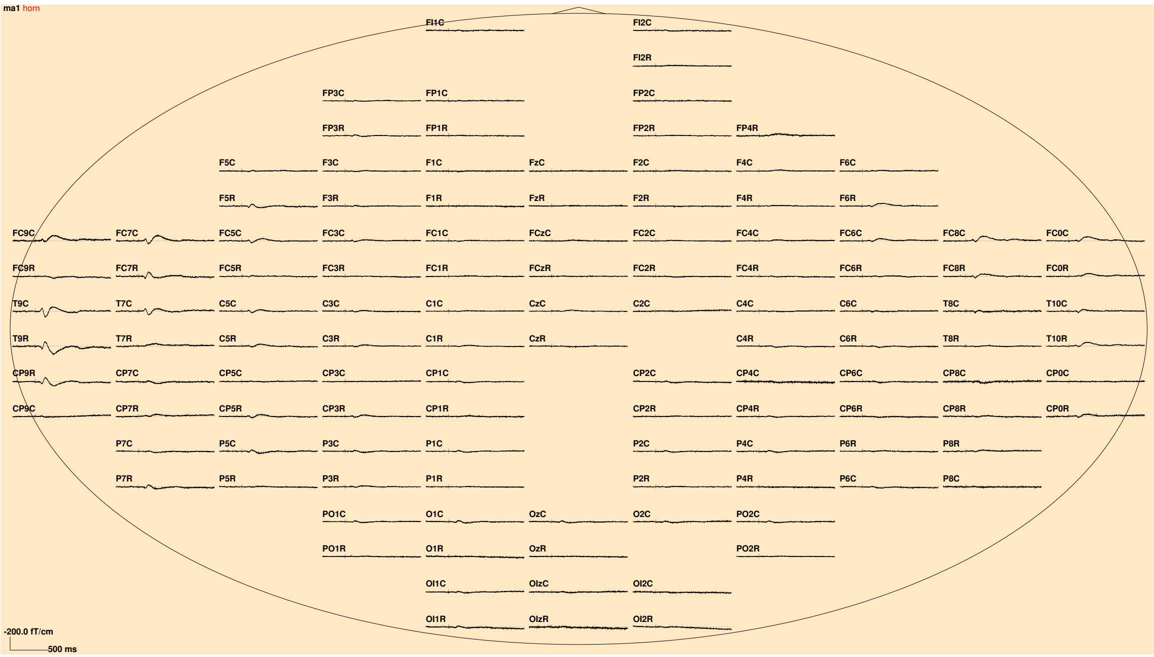
Table 4.8: Dipole localization of components

The exact dipole localizations for each component (P1, N1, P2, SF) and their differences between the groups are presented in Talairach coordinates.

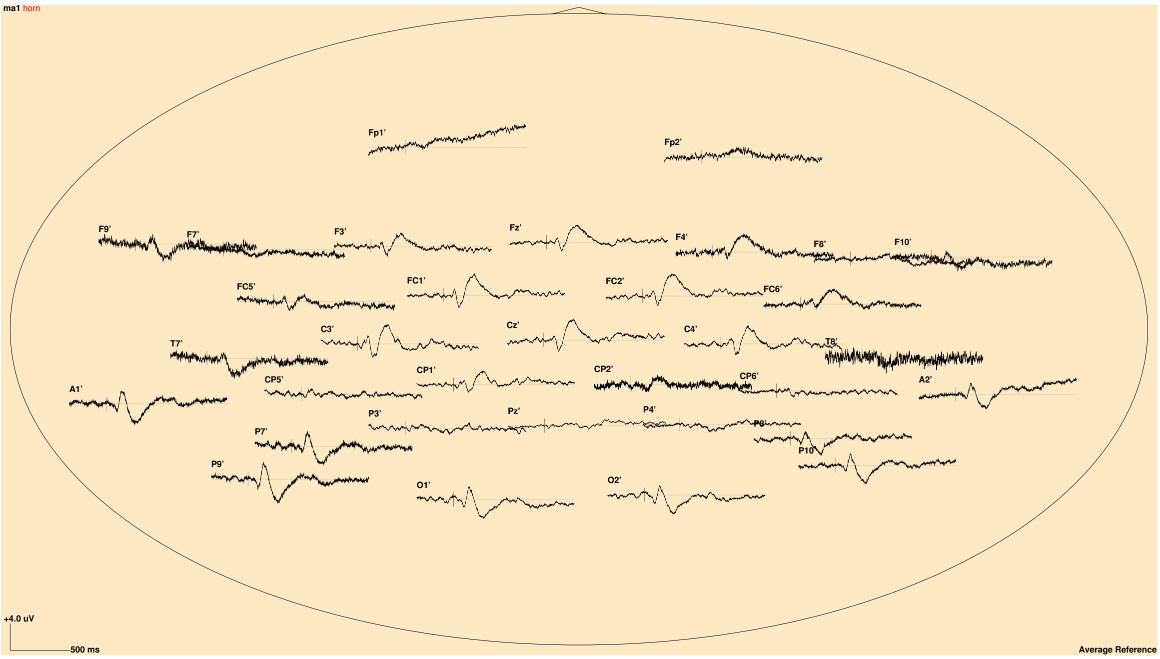
4.3. Individual MEG and EEG Measurement

We wondered if the lack of sustained field in some German subjects might have been due to anatomical peculiarities resulting in radial currents which would not create any magnetic field, as mentioned in Sec. 2.3. Since radial currents are visible in EEG measurements, a simultaneous MEG and EEG measurement for one individual subject was performed in another session. For this purpose we used the paradigm of the second experiment to take a look at the neural responses of the linguistic stimulus /ma1/ and the musical stimulus of the horn. Since we knew that we needed to exclude artifacts due to eye blinking from the EEG data, we prolonged the original 8 min to a 75 min session. Despite the exclusion, a high amount of about 1100 averages led to an accurate data analysis without filtering.

In Fig. 4.19 and 4.20, the top views of all gradiometers of the MEG and electrodes of the EEG are presented. Since the MEG signals in these figures are very small, a zoom was performed on the auditory cortex where the neurons showed higher activity than in other regions. Because the activity is nearly symmetric for both hemispheres, it is sufficient to only take a closer look on the left auditory cortex in Fig. 4.19c. Please note that MEG and EEG top views show different measurements. The gradiometer of the MEG measure the gradients of the magnetic fields in fT/cm, while the EEG measures the potential differences to a reference electrode. As mentioned earlier in Sec. 2.3, the top view of our MEG with planar gradiometers shows considerably the localization of activity within the brain. The localization of activity in EEG does not work as good as in MEG so that we should not mistake the measurements of the electrodes for the actual activity in this region. The actual activity can be seen from the dipole analysis, see Fig. 4.21, which shows the average dipole waveform for MEG and EEG. The remarkable agreement, especially in the region of the sustained field, gives additional confidence in the significance of the MEG measurements.



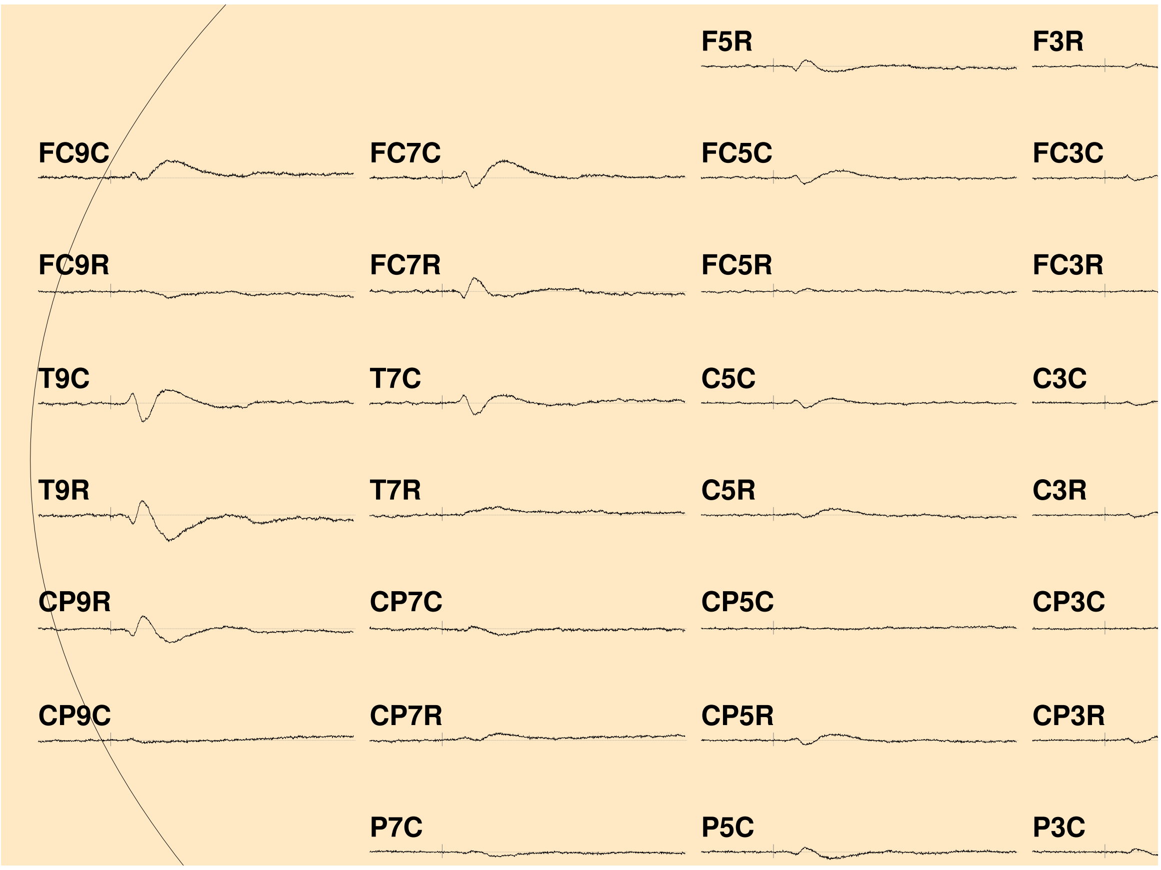
(a) MEG



(b) EEG

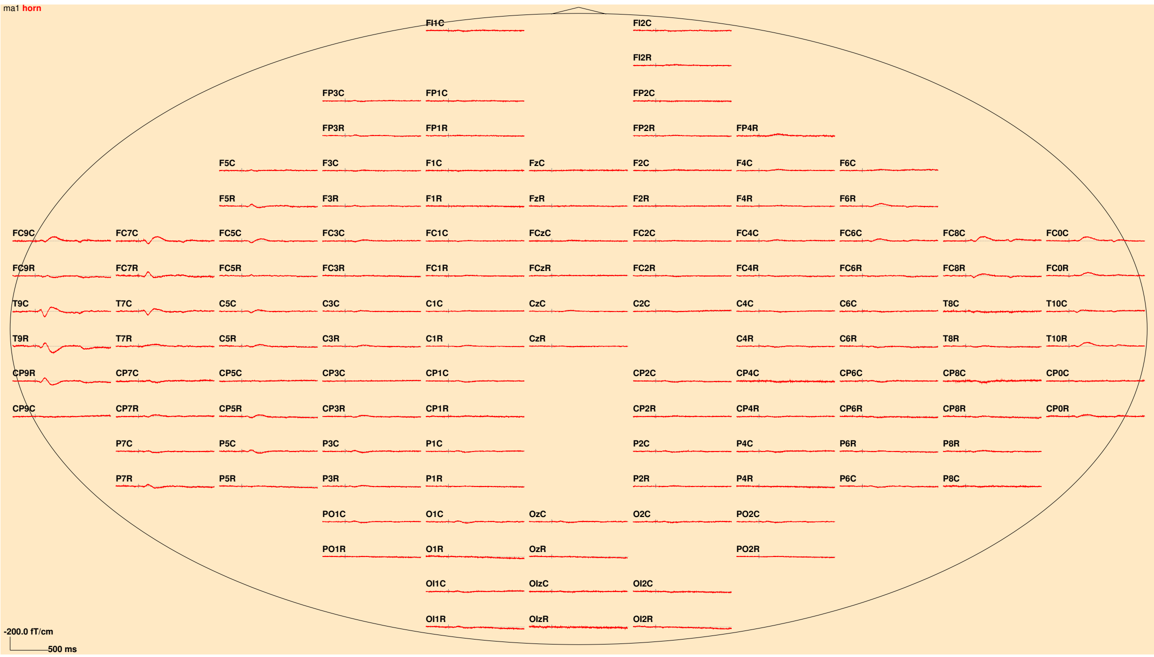
Figure 4.19: MEG and EEG top view of individual for stimulus /ma1/

The gradiometer of the MEG measure the gradients of the magnetic fields in fT/cm, while the EEG measures the potential differences to a reference electrode in V. In 4.19a the MEG top view shows a higher activity in the auditory cortex than the other regions of the brain. The localization of activity in EEG does not work as good as in MEG so that we should not mistake the measurements of the electrodes in 4.19b for the actual activity in this region.

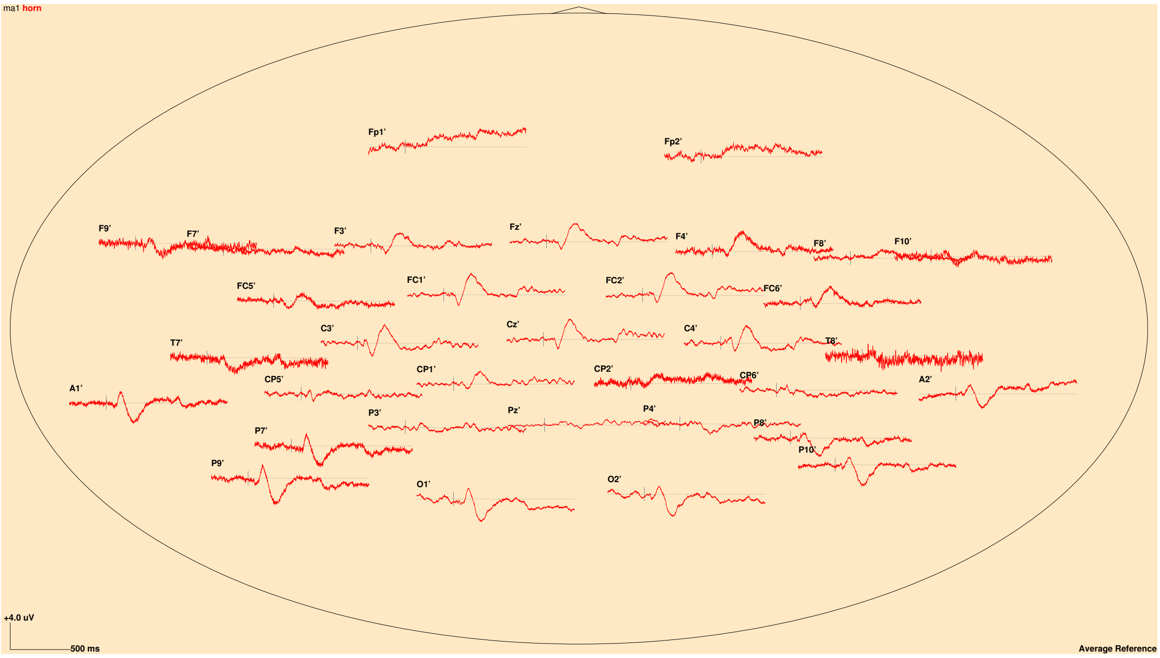


(c) Zoom into MEG topview

Figure 4.19: MEG and EEG top view of individual for stimulus /ma1/ (cont.) Since the MEG signals in the top view are very small, a zoom was performed on the auditory cortex where the neurons actually showed activity. Because the results are symmetric for both hemispheres, it is sufficient to take a closer look on the left auditory cortex in 4.19c.



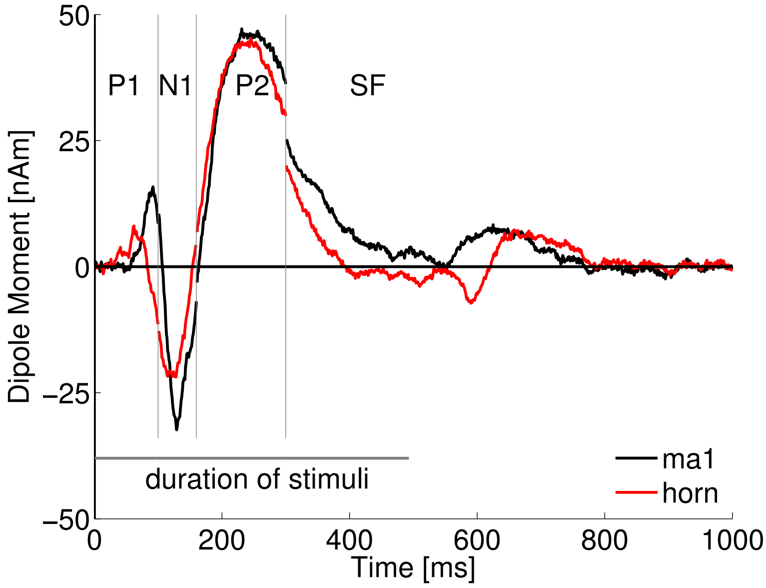
(a) MEG



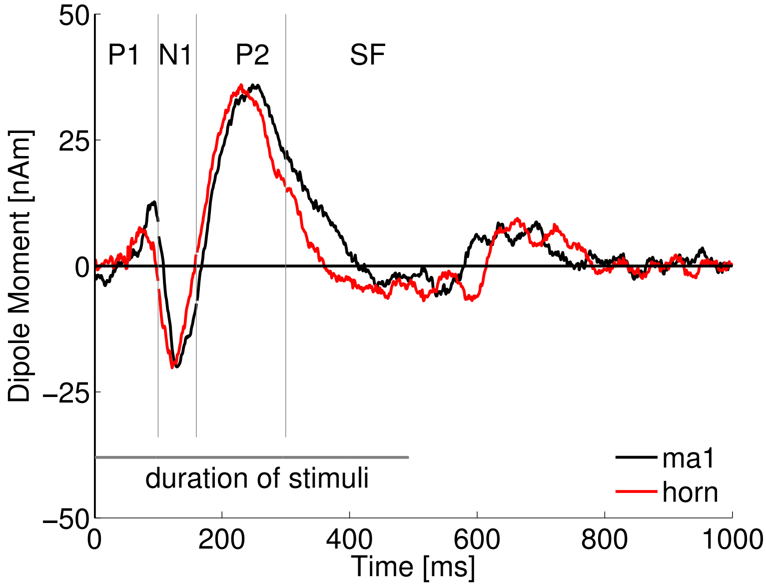
(b) EEG

Figure 4.20: MEG and EEG top view of individual for horn stimulus

The results of the horn stimulus look quite similar to those of the linguistic stimulus /ma1/.



(a) **MEG**



(b) **EEG**

Figure 4.21: Average dipole waveform of individual for MEG and EEG

In this figure, the average waveforms of separate 2-dipole models for the MEG and EEG data are displayed. Again, the graphs of both groups are compositions of several waveforms. Comparing these two curves, it is remarkable how similar they look. The interesting component of the sustained field is not larger in the EEG measurement.

4.4. Multiple Individual MEG Measurements

Additionally to the parallel MEG and EEG measurement of an individual, multiple MEG measurements were performed on another individual to evaluate the fluctuations within an individual subject. The consistency of an individual subject was examined by conducting ten MEG measurements on the Chinese subject (PX). The paradigms consisted of the session with the syllables /ma/ and /mu/ as well as the session with the syllable /ma1/ and a French horn tone, which are the same as in the main experiments from Sec. 4.1. In Sec. 3.1, the characteristics of the stimuli are given in detail. The measurements were taken within 15 days. See also Sec. A for additional individual measurements concerning the stability of individual measurements as well as the effect of sound levels on the location and amplitude of dipoles of different stimuli. The measurements were performed as a prestudy to this dissertation using the paradigm from my diploma thesis.

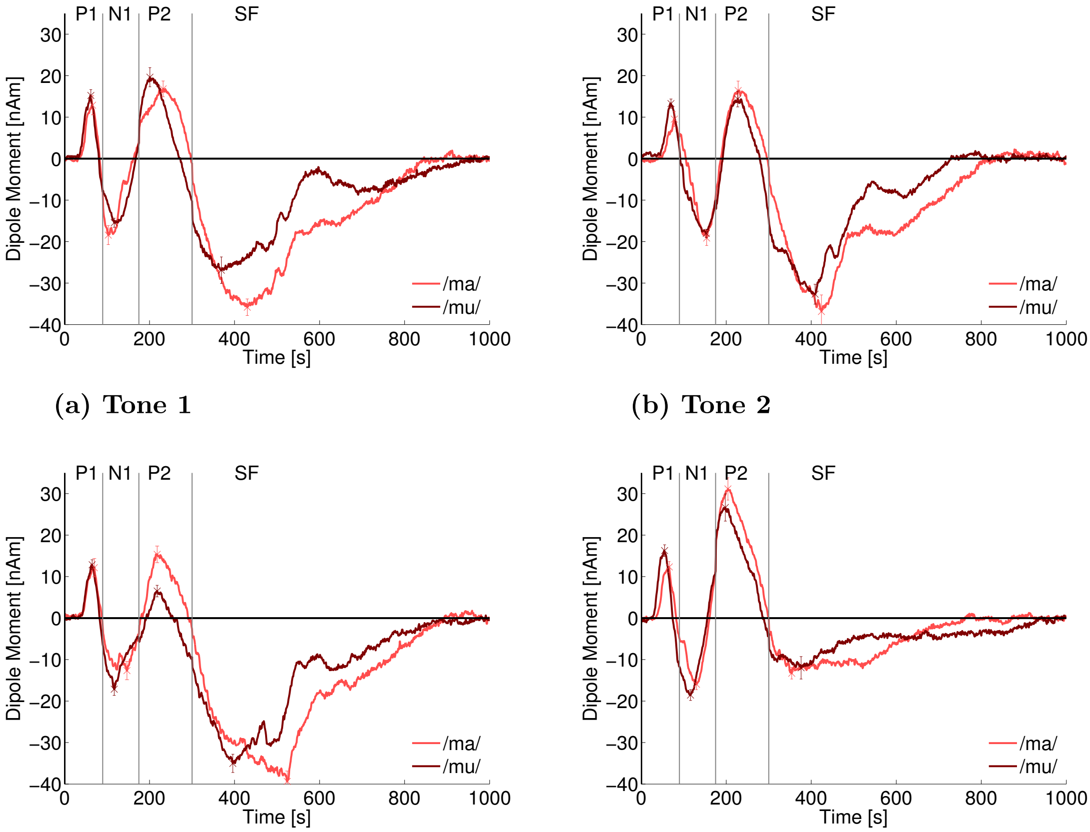
Data analysis for the multiple individual MEG measurements of this dissertation was performed according to Sec. 3.3 with the focus on the 2-dipole model. Statistically, paired two-tailed Student's t-tests were performed on the data. The degree of freedom is $\nu = 9$.

4.4.1. Dipole Waveforms

The semantic effect that was found for the integrated sustained fields within the entire Chinese group (see Tab. 4.4) could be confirmed for subject PX. The largest difference between the sustained fields of the subject PX could be found for the pair of meaningful syllable /ma1/ and meaningless syllable /mu1/ ($\Delta(ISF_{ma1} - ISF_{mu1}) = -3.0 \pm 0.6\,\text{nAm}\cdot\text{s}$, $t_{ISF,T1}(9) = 3.82$, $P_{ISF,T1} = 0.004$, $t_{SF,T1}(9) = 2.71$, $P_{SF,T1} = 0.02$). The syllables /ma3/ and /mu3/ also exhibit a large difference in their integrated sustained field ($\Delta(ISF_{ma3} - ISF_{mu3}) = -2.3 \pm 0.7\,\text{nAm}\cdot\text{s}$, $t_{ISF,T3}(9) = 2.46$, $P_{ISF,T3} = 0.04$) but the difference of the SF peak only is not significant ($\Delta(SF_{ma3} - SF_{mu3} = -3.9 \pm 3.3\,\text{nAm}$, $t_{SF,T3}(9) = 1.16$, $P_{SF,T3} = 0.27$). The other pairings did not show any significant differences in sustained field between the syllables /ma/ and /mu/.

Subject PX exhibits significant differences between the P1 components of the meaningful syllables /ma2/ and /mu2/ ($t_{P1,T2}(9) = 4.40$, $P_{P1,T2} = 0.002$) as well as /ma4/ and /mu4/ ($t_{P1,T4}(9) = 3.11$, $P_{P1,T4} = 0.01$). The P2 components of the meaningful syllables /ma3/ and /mu3/ differ also significantly ($t_{P2,T3}(9) = 5.08$, $P_{P2,T3} = 0.001$), which we do not understand.

Unlike the results from the average over all Chinese subjects which did not differ much between linguistic and musical stimulus, the individual subject PX does indeed show large differences between both stimuli ($t_{PX}(9) = 9.08$, $P_{PX} = 10^{-4}$), see Fig. 4.2.



(a) Tone 1 **(b) Tone 2** **(c) Tone 3** **(d) Tone 4**

Figure 4.1: Composition of dipole waveforms of the Chinese subject PX for each tone of the syllables /ma/ and /mu/

As in Fig. 4.17 each partition is a result of another pair of freely fitted effective dipoles on the respective component (P1, N1, P2, SF). Thus, the composition of these four different dipole waveforms, one in each partition, is displayed for each tone. The error bars are from the standard error of mean.

For the N1 component, there are no differences between the syllables /ma/ and /mu/. The most striking difference can be seen for the sustained field (SF) between the meaningful syllable /ma1/ and meaningless syllable /mu1/. Contrary to the entire Chinese group, it is not the only difference between the paired syllables /ma/ and /mu/.

Dipole moment [nAm]

	ma1	**mu1**	**Δ(ma1,mu1)**	**ma2**	**mu2**	**Δ(ma2,mu2)**
P1	14.5 ± 1.2	16.4 ± 1.4	-2.0 ± 1.2	10.8 ± 1.2	15.2 ± 1.1	-4.4 ± 1.0
N1	-21.8 ± 2.3	-20.1 ± 1.1	-1.8 ± 2.1	-23.2 ± 1.8	-21.9 ± 1.0	-1.3 ± 1.6
P2	20.0 ± 1.9	23.0 ± 2.3	-3.0 ± 1.6	19.7 ± 2.3	18.0 ± 1.9	1.7 ± 1.2
SF	-39.2 ± 2.0	-30.6 ± 3.2	-8.7 ± 3.2	-39.5 ± 4.0	-35.1 ± 2.4	-4.5 ± 4.2

(a) Tones 1 and 2

Dipole moment [nAm]

	ma3	**mu3**	**Δ(ma3,mu3)**	**ma4**	**mu4**	**Δ(ma4,mu4)**
P1	14.3 ± 1.4	14.3 ± 1.2	-0.1 ± 1.3	13.7 ± 1.4	17.7 ± 1.4	-4.0 ± 1.3
N1	-18.7 ± 2.2	-19.5 ± 1.5	0.8 ± 2.0	-20.5 ± 1.3	-22.1 ± 1.3	1.6 ± 1.3
P2	18.0 ± 2.0	9.2 ± 1.4	8.7 ± 1.7	33.3 ± 2.7	29.4 ± 3.3	3.9 ± 2.0
SF	-41.7 ± 2.5	-37.9 ± 2.2	-3.9 ± 3.3	-16.6 ± 1.4	-15.6 ± 2.7	-1.1 ± 2.9

(b) Tones 3 and 4

Table 4.1: Transient and sustained components of dipole waveforms (PX) As expected from the results of the entire Chinese group, PX shows large differences between the sustained fields of the meaningful syllable /ma1/ and the meaningless syllable /mu1/ (Δ(ma1-mu1) $= -8.7 \pm 3.2$) but PX also shows significant differences between components of other matched pairs.

4.4.2. Localization

As can be seen in Figure 4.3, the standard error of mean for one single person is much smaller than for the group. This is in line with our expectations as the deviation within an individual subject should always be smaller than between different subjects.

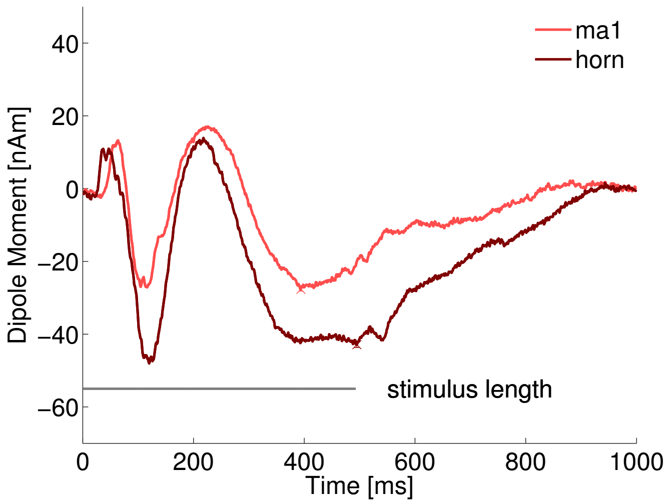
The subject PX does not fall into the vicinity of the other Chinese subjects as PX's generators are always posterior to theirs for all components, see Fig. 4.3.

As the other Chinese subjects, PX shows a difference in x-direction between the N1 and SF component as the generators of SF are medial to the generators of N1, see Tab. 4.8 and Fig. 4.4.

ISF [nAm · s]	ma	mu	Δ(ma,mu)
Tone 1	-10.0 ± 0.4	-7.0 ± 0.6	-3.0 ± 0.6
Tone 2	-8.7 ± 0.8	-6.2 ± 0.4	-2.5 ± 0.8
Tone 3	-11.3 ± 2.4	-9.0 ± 0.3	-2.3 ± 0.7
Tone 4	-3.5 ± 0.6	-3.4 ± 0.5	-0.1 ± 0.6

Table 4.2: Semantic effect of ISF (PX)

The semantic effect that was found within the entire Chinese group (see Tab. 4.4) is not as strong for subject PX. Although the largest difference between the integrated sustained fields of the subject PX can be found for the pair of meaningful syllable /ma1/ and meaningless syllable /mu1/ (Δ(ma1-mu1) = -3.0 ± 0.6, $t_{ISF,T1}(9) = 3.82$, $P_{ISF,T1} = 0.004$), the other pairing of /ma3/ and /mu3/ also shows significant differences in ISF but not in SF.



ISF [nAm · s]	PX	all Chin
/ma1/	-7.2 ± 0.5	-13.3 ± 1.1
horn	-15.8 ± 0.8	-17.3 ± 2.1
Δ(ma1,horn)	8.7 ± 0.7	4.0 ± 2.1

Figure 4.2: Linguistic vs musical stimuli (PX)

Unlike the results from the average over all Chinese subjects which did not differ much between linguistic and musical stimulus, the individual subject PX does indeed show significantly large differences between both stimuli ($t_{PX}(9) = 9.08$, $P_{PX} = 10^{-4}$).

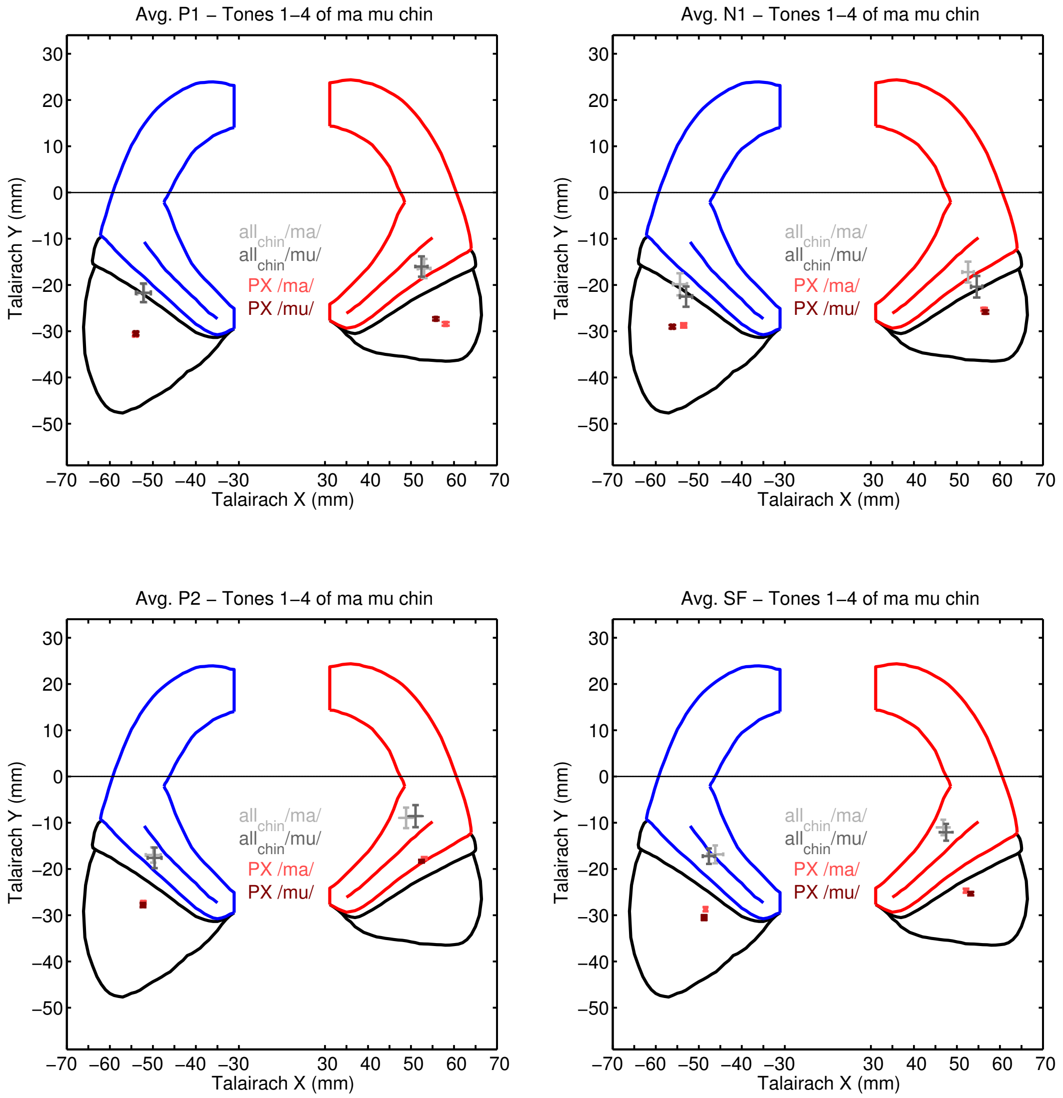
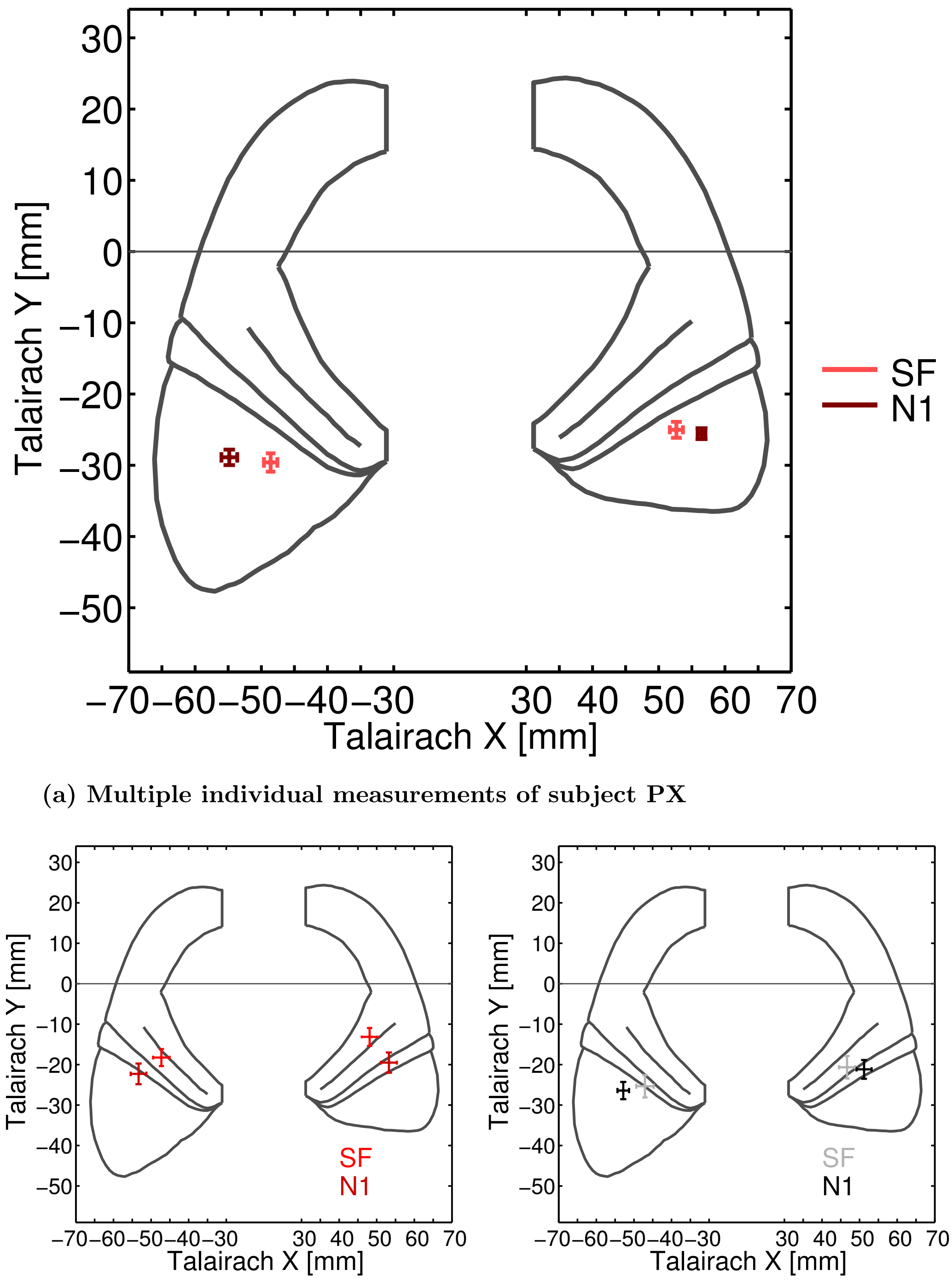


Figure 4.3: Localization of dipoles (PX)

A 2-dipole-model with freely fitted dipoles in the left and right hemispheres was applied. This figure shows a comparison of the dipole localizations of the Chinese subject PX to the Chinese group. The error bars are from the standard error of mean. As can be seen in these figure, the standard error of mean for one single person is much smaller than for the group.



(a) Multiple individual measurements of subject PX

(b) Main Chinese group

(c) Main German group

Figure 4.4: Comparison of N1- and SF-Localizations

The figures show a 2-dipole-model with freely fitted dipoles in the left and right hemispheres. (a) the dipole localizations of the sustained field of the subject PX are more medial than the N1 dipole localizations. The same is true for the main experiments with 20 Chinese (b) and 20 German subjects (c).

5. Discussion

The major result of this dissertation is the difference of the sustained field between German and Chinese subjects evoked by natural speech sounds. It suggests that differences between the phonological systems in the subjects' mother tongue have a major impact on auditory processing at the level of the auditory cortex. An important difference between the phonological system in Mandarin Chinese and German is the use of pitch variation in a syllabic context, namely in the function of lexical tone for discriminating meaning. Beside this difference in the phonological system, single syllables typically form words in Chinese and thus carry meaning, in contrast to German. Taken together, it seems that the importance of syllables for carrying meaning, and the importance of pitch variation for discriminating meaning in particular, lead to marked differences in sustained field between both groups. In the Chinese group there is a statistically significant difference between the responses evoked by meaningful as compared to meaningless syllables. All this provides strong evidence that the sustained field differences between Chinese and German listeners reflect differences in speech processing. It can be concluded that the generators of the sustained field reflect two processes: one at the phonological level, which is sensitive to general acoustic features of natural speech, and one on the semantic level, sensitive to meaning. These observations suggest that the sustained responses represent an important parameter for the assessment of both phonological and semantic processing.

Our results that the main differences between the two language groups are reflected in the sustained field magnitude and morphology (see Sec. 4.1 and Fig. 4.2) mirrors previous findings on sound processing at the subcortical level, as provided by Krishnan et al. (2009a,b, 2010) and others (Song et al., 2008; Swaminathan et al., 2008), as mentioned earlier in Sec. 2.4. Based on the analysis of frequency following responses (FFR), which originates from the auditory brainstem, they observed a higher pitch-tracking accuracy as well as a more robust pitch-strength representation over the whole duration of speech sounds for speakers of tonal languages (Chinese, Thai), compared to speakers of non-tonal languages (English), see Fig. 2.16. Since the sustained portions of such measures are derived from waveforms of speech sounds with specific pitch contours that last for several hundred Milliseconds, the FFR generator at some early level of the brainstem might be closely related to the sustained field at the cortical level, which is presumably generated in areas beyond primary auditory cortex (Gutschalk and Uppenkamp, 2011). Although the major differences of FFR between groups of speakers with tonal and non-tonal languages suggest that such differences are driven by linguistic experience, FFR per se do not reflect differences between speech and non-speech stimuli, since several studies clearly show that long-term musical experience also influences FFR (Musacchia et al., 2007) and pitch representation in the brainstem is not specific to speech context because frequency-following responses also occur for iterated rippled noise sounds that have the same pitch contour as the tones but without speech itself (Swaminathan et al., 2008). This is in line with the assumption that speech-specific processing occurs at higher stages in the auditory cortex and adjacent areas. In these areas we observed indeed differences for linguistic and musical stimuli: While linguistic stimuli elicited different sustained field in Chinese and German subjects, no differences between the groups were observed for the musical stimulus. However, the current data does not provide any basis to disentangle the causal relationship between brainstem and cortical responses. In order to further clarify the details of the relation between sustained field and FFR, it is necessary to conduct long-term studies which employ coregistration of brainstem and cortical responses within the same sessions.

Regarding the phonological status of the vowels in the linguistic systems of Chinese and German, we tested /o/ against /ö/, where the latter is not part of the Chinese vowel system, see Sec. 3.1 and 4.1.1. As expected, no difference was observed in the activation patterns of the German subjects, but there was also no difference in the neural responses of the Chinese speakers with respect to the two vowels. This result indicates that the large sustained field difference between groups is not related to habituation to specific stimuli, but rather to the structure of the stimulus. Although Chinese listeners are not habituated to the vowel /ö/, they are accustomed to its temporal and structural property, e.g. the rich harmonic spectrum as reflected in the formant dynamics, which it shares with other vowels.

Our result that tone processing in the auditory cortex does not seem to be affected by the phonological status of the vowel in the respective linguistic systems differs from studies concerning the cortical transient response of mismatch negativity (MMN). As briefly discussed in the introduction, phoneme systems studies have shown larger MMN responses for phonemes that occur in the subjects' mother tongue compared to those that do not (Chandrasekaran et al., 2009b,a; Näätänen et al., 1997; Fournier et al., 2010). The different pattern in mismatch negativity and sustained field for habituated stimuli indicates an independent mechanism. This is not astonishing, since the mismatch negativity depends on the structure of the stimuli in the past, whereas the task of detecting a varying pitch is strictly confined to the duration of the stimulus. There are only a few MEG studies investigating differences between Chinese and non-Chinese speakers. Valaki et al. (2004) compared the group-specific lateralization of Chinese, English and Spanish speakers around 200ms after stimuli onset while the subjects performed a word recognition task. Their results suggest increased participation of the right temporoparietal region in spoken word recognition in Chinese. Lin et al. (2005) found a larger amplitude ratio of speech to non-speech N1m in the left compared to the right hemisphere for Chinese subjects. In our experiment, where the subjects listened passively to the stimuli, no significant lateralization was found for either the SF nor for the transient signals. This is in accordance with other results which indicate that phonological stages of spoken word recognition is supported by neural systems in the superior temporal lobe bilaterally (Hickok, 2009).

Our observation of language-related contrasts in sound processing at the cortical level poses the question as to the nature and level of the language-specific influence. In order to provide an answer we investigated the meaningless (/mu1/) and meaningful (/ma1/) minimal pair compared to meaningful pairs (/ma2/-/mu2/, /ma3/-/mu3/, /ma4/-/mu4/), differing in vowels carrying the same pitch contour. Chinese subjects produced significantly stronger sustained fields for the meaningful syllable /ma1/ than for the meaningless syllable /mu1/ (see Fig. 4.10), while all other meaningful pairs of syllables evoked sustained fields of comparable size. German subjects did not show significant differences with respect to any pairs of syllables. This indicates that the difference is in fact due to the meaningfulness related to a specific syllable-tone cluster for Chinese speakers and not to pitch processing as a mere physiological reflection of a physical signal. This brings us a step forward to interpreting language-related differences. In addition to possible patterns developed in the course of language acquisition, which do not need cognitive correlates for activation, we also see evidence for language-specific effects on pitch perception which are rooted at higher levels, i.e. cognitive processing. These findings point to the relevance of top-down processing in speech perception. Further evidence for a top-down effect contribution is temporal behavior. Comparing the time dependence of the sustained field for the meaningful syllable /ma1/ and meaningless syllable /mu1/ in the Chinese group (Fig. 4.11), we see that the asymmetry of the sustained field starts at about 400 ms. This is in line with the commonly assumed time window for semantic processing (Kutas and Hillyard, 1980). This evidence for top-down effects is supported by studies looking at language-related neuroanatomical structures. Evidence for massive top-down effects is given by the ratio of afferent and efferent connections which is reported to be about 1:4 (Popper and Fay, 1992; Nelken, 2008).

Kutas and Hillyard (1980) used seven-word sentences with the last word being either semantically inappropriate with different degrees of inappropriateness, or semantically correct and expected, to identify the N400 component which was elicited by semantically inappropriate words in reading tasks which starts at ~ 250 ms, peaks at 400 ms and lasts until 600 - 800 ms. They assume the degree of semantic unexpectedness to be responsible for this negative component. Despite obvious similarities in temporal behavior, the sustained field that was investigated in this dissertation exhibits different characteristics. First of all, it would be very surprising to see a N400 component due to our paradigms because we did not use any sentences nor sentence fragments which could arise semantic expectations. There was no certain order of tone and syllable or vowel because the stimuli were randomly presented. None of the Chinese subjects perceived any sentences or sentence fragments. They only heard certain words in the syllable paradigm and could not make any sense to the vowel paradigm. Furthermore, the vowels /o/ and /ö/ do not contain any meaning, the latter does not even exist in the Chinese phonetic system. Even assuming possible associations to meaningful syllables for the vowel /o/ through rhymes, this certainly would not have occurred for the vowel /ö/. Besides, there was no lateralization to be measured for our data in contrast to the N400 component whose lateralization effect leads to larger responses in the right hemisphere (Kutas and Hillyard, 1982; Boddy, 1986; Kutas et al., 1988). In addition to that, the temporal progress of the dipole waveforms of this dissertation show an integrative character, as there is correlation between integrated sustained field and the length of the stimuli contrary to expectations to the N400 component.

Our stimuli were rather short because we were also interested in transient components as well as possible future FFR measurements with the same set of stimuli. If we focussed entirely on the sustained component, we could use stimuli of longer duration which would still have to be perceived as natural speech. We think that this would create stimuli with a sustained plateau rather than a negative peak and thus the confusion between sustained field and N400 would be resolved. This will be part of a future dissertation.

The results from the vowel study considering /o/ and /ö/, as discussed above, seems to contradict the results for meaningful and meaningless syllables insofar as vowel-related linguistic knowledge does not come into play when processing pitch on a segmental level. However, vowels as segments are not meaningful. This could explain the difference in reaction to the meaningful syllables. This would denote that as long as meaning is not involved, different phonological components of speech signal are processed separately according to language-specific principles of relevance.

In pursuing the question of language specificity in pitch perception we tested the neural signals evoked by musical versus linguistic stimuli in a further step. Listening to the musical stimulus produced by a French horn, Chinese subjects showed an integrated sustained field similar to the German group. This supports the assumption that our main result, the significant difference in sustained field for Chinese and German subjects, is a result of a language-related filter.

An interesting line of research is opened up by the investigation of the location of the effective dipoles generating the sustained field. Belin et al. (1999) employed functional magnetic resonance imaging and characterized bilateral voice-selective regions in the upper bank of the superior temporal sulcus (STS), a finding that has been corroborated by subsequent studies (Binder et al., 2000; Davis and Johnsrude, 2007; Gutschalk and Uppenkamp, 2011). Systematic anatomical studies between humans and macaques suggest that this region represents some late-stage auditory processing (Kaas et al., 1999). The position of the effective dipole generating the sustained field is for Chinese closer to the vowel- and pitch-specific region found by Gutschalk and Uppenkamp (2011), whereas for Germans it is closer to the non-specific domain.

The fact that the generators of the Chinese subjects are always anterior to the German subjects, no matter which component is examined, leads to the assumption that the difference between the groups might be an anatomical difference. Since in our investigation, there were only averages obtained with a spherical head model which were not adopted to individual anatomy, we still have to be careful not to draw early conclusions. To confirm the difference in dipole localization between German and Chinese, MRI would be an appropriate tool for future measurements.

Taken together, the results of our studies support our initial hypothesis that speech sound activates a language-specific filter. This can be partly incorporated into highly automated and high speed processes developed in the course of language acquisition, perhaps by speech stimulus-dependent neurons (Wollberg and Newman, 1972; Wang et al., 2005). This would explain the roughly constant ratio of the integrated sustained fields for Chinese and German listeners to speech stimuli. After the earlier phase distinguishing between speech and non-speech a slower process at a later phase corresponds to the meaningfulness of the linguistic stimulus.

The specific N1- and SF activation pattern, as exhibited in Fig. 4.18 is in line with the observations of Okamoto et al. (2011) who observed that these components depended to a different degree on top-down and bottom-up processes. While earlier components such as amplitude modulated steady-state responses, as well as the N1m, tended to reflect acoustic features of sounds, the SF depended to a much higher degree on attention, i.e. presumably on top-down influences. This dichotomous behavior was also found in our analyses: While the transient N1 evoked by the onset was of comparable amplitude in both groups, the SF - which is suggested to reflect complex feedback loops - differed substantially for linguistic stimuli. The additional observations that (i) we did not find SF differences between groups for the horn tone, and (ii) that we observed a significant difference of the /ma1/-/mu1/ contrast for Chinese listeners, reflects an additional characteristic of genuine top- down processes as proposed by the Reversed-Hierarchy-Theory (RHT) (Hochstein and Ahissar, 2002; Nelken and Ahissar, 2006). According to this theory, a high-level response is assumed to be late in the bottom-up hierarchy and is suggested to show some strong dependency on temporal contexts. Both characteristics are nicely reflected by the specific sustained field behavior. Thus the sustained field is a promising component offering clues to language-related auditory processing. How language driven top-down processes exactly interact with automated physical responses in early auditory processing remains to be studied in the future. Since the sustained field does not seem to be well-represented in metabolism-based methods like functional magnetic resonance imaging (Gutschalk and Schadwinkel, 2009; Gutschalk and Uppenkamp, 2011), the more direct non-invasive methods MEG and EEG must play an important role in these investigations.

An additional EEG measurement for a subject with only small sustained field in the MEG revealed no sudden sustained component in EEG which means that radial currents were not responsible for the lack of sustained field in this subject, see Sec. 4.3.

There are plenty of investigations concerning the P1 and P2 components of dipole waveforms which link them to musicality (Schneider et al., 2002; Shahin et al., 2003). A short look at the Advanced Measure of Music Audiation (AMMA) of 15 German subjects, which is a short test for musicality by Gordon (1989), however, did not show any correlation between musicality and neither P1 ($\rho_{P1} = 0.07$), P2 ($\rho_{P2} = 0.3$) nor SF components ($\rho_{ISF} = 0.1$). The differences between the P2 components of the German and Chinese subjects might be explained by the large differences in sustained field. Large sustained fields could possibly pull down the P2 component as well. Another indication for this are the high-pass filtered dipole waveforms in Fig. 4.13 in Sec. 4.1.1 which only leave the transient components that do not exhibit any differences between the groups.

Even though the significant result of differences between the Chinese and German group might mislead to the assumption that it is possible to distinguish Chinese from German speakers by the size of the sustained field, with the distribution of integrated sustained fields among both groups in mind, it is difficult to distinguish Chinese and German speakers merely by the size of their sustained field. A closer look at the distribution ISF shows a large overlap between German and Chinese subjects, see Fig. 4.7. Some Germans have an even larger ISF than some Chinese subjects. The question of why they do and what it means has to be answered in further studies. Possible anatomical differences and connections to the natural ability of perceiving Chinese tones are conceivable.

Since our stimulation comprised only monosyllabic words, the next step would be to look at responses to short sentences consisting of two or more words. In this vicinity so-called tone sandhi might occur. These are typically words that change their pitch contour from one tone to another in natural speech depending on the next word in the sentence. This will be part of Xingyu Zhu's dissertation.

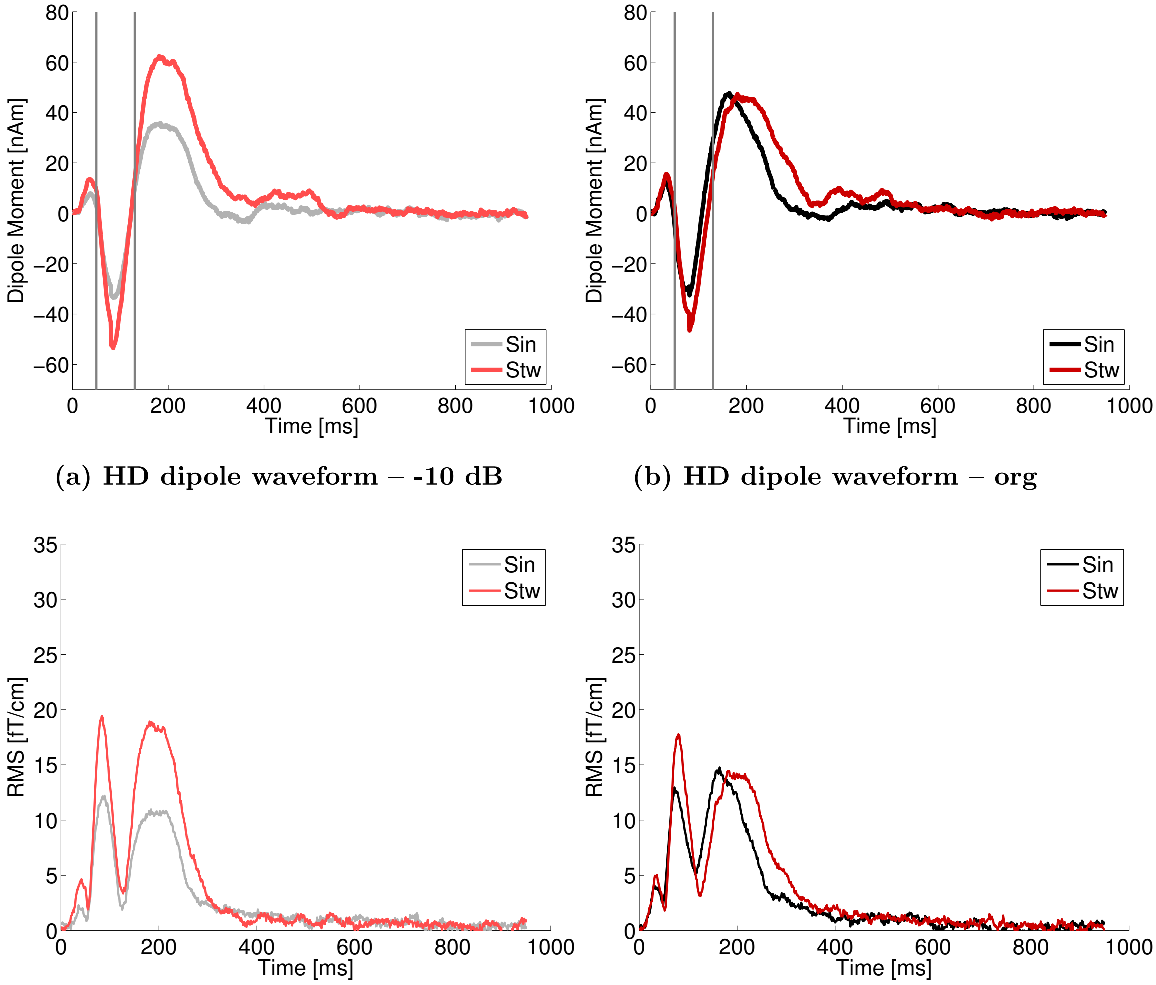
His future research project will also embed the comparison of responses to native German and Chinese monosyllabic words. As mentioned in the introduction, German intonation also contains pitch contours. Depending on the situation, the German word "Ja" (yes) can be pronounced similarly to Chinese tones – it can sound bored and annoyed (Tone 1), inquiring

(Tone 2), contemplative (Tone 3) or approving (Tone 4). By comparing responses to both sets of stimuli might lead to enlarged sustained fields in the respective native subjects.

Appendix

A. Prestudy

Similar to Sec. 4.4, where multiple individual measurements were performed on an individual subject to evaluate the fluctuations within an individual subject, I measured two individuals in a prestudy to this dissertation.
In order to investigate the stability of an individual measurement of a single subject and the effect of sound levels on the location and amplitude of dipoles of different stimuli, I measured two subjects for six and eight times.
I prepared a set of four stimuli – two of them I investigated in my diploma thesis Fan (2009): a sinusoidal tone (440 Hz, 700 ms, 68 dB SPL) and a Steinway tone of the same frequency, length and intensity. For the purpose of this study, I reduced the sound level by 10 dB which is about half as loud as the original stimuli. These stimuli were the other two missing stimuli of the set. About 250 signals were averaged for each subject, component, and fit. The data analysis was basically the same as in Sec. 3.3.
The average dipole waveforms of the N1 fit as well as the root-mean-square of all gradiometer are displayed for the subjects HD and MA in Fig. A.1 and A.2. Both methods of data analysis agree well with each other. Larger RMS signals also correspond to larger N1 components of the dipole waveforms. Subject MA has very consistent dipole waveforms for the original stimuli and those with 10 dB less intensity, while subject HD's signals for the piano tone are reduced when the intensity is reduced. In Tab. A.1-A.6, the individual components of each measurement as well as their averages and standard errors are presented for the applied 2-dipole model.
As can be seen in Figure A.3, the localization for a 2-dipole model is approximately the same for the sinusoidal and Steinway tone. The sound level of the stimuli is also not crucial for the dipoles' localizations.
The P1 component is by far the most difficult transient component to adjust a 2-dipole model because it is much smaller than the N1 or P2 components.



(a) **HD dipole waveform – -10 dB**

(b) **HD dipole waveform – org**

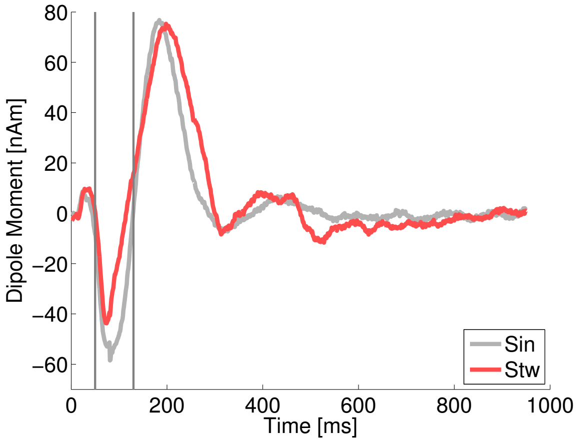
(c) **HD RMS – -10 dB**

(d) **HD RMS – org**

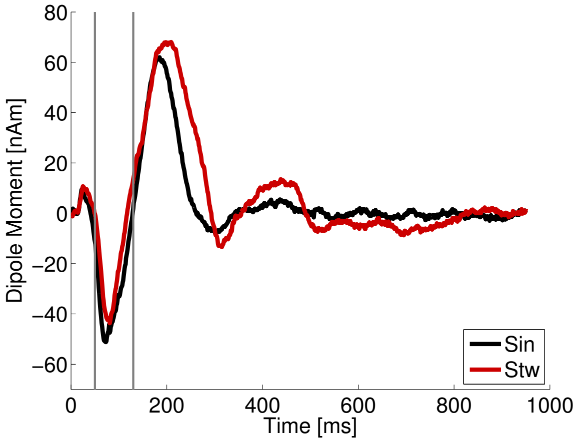
Figure A.1: Multiple individual measurements of HD

The combination of average dipole waveforms of the fits around the P1, N1 and P2 components as well as the root-mean-square of all gradiometer are displayed for the mentioned set of stimuli for the subject HD.

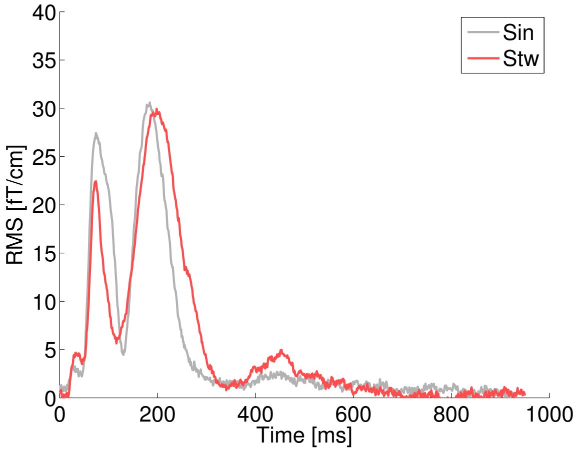
Both methods of data analysis agree well with each other. Larger RMS signals also correspond to larger N1 components of the dipole waveforms.



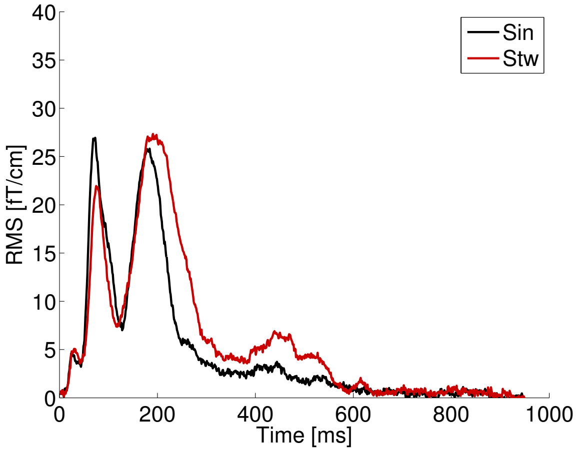
(a) MA dipole waveform – -10 dB



(b) MA dipole waveform – org



(c) MA RMS – -10 dB



(d) MA RMS – org

Figure A.2: Multiple individual measurements of MA

The combination of average dipole waveforms of the fits around the P1, N1 and P2 components as well as the root-mean-square of all gradiometer are displayed for the mentioned set of stimuli for the subject MA.

Both methods of data analysis agree well with each other. Larger RMS signals also correspond to larger N1 components of the dipole waveforms.

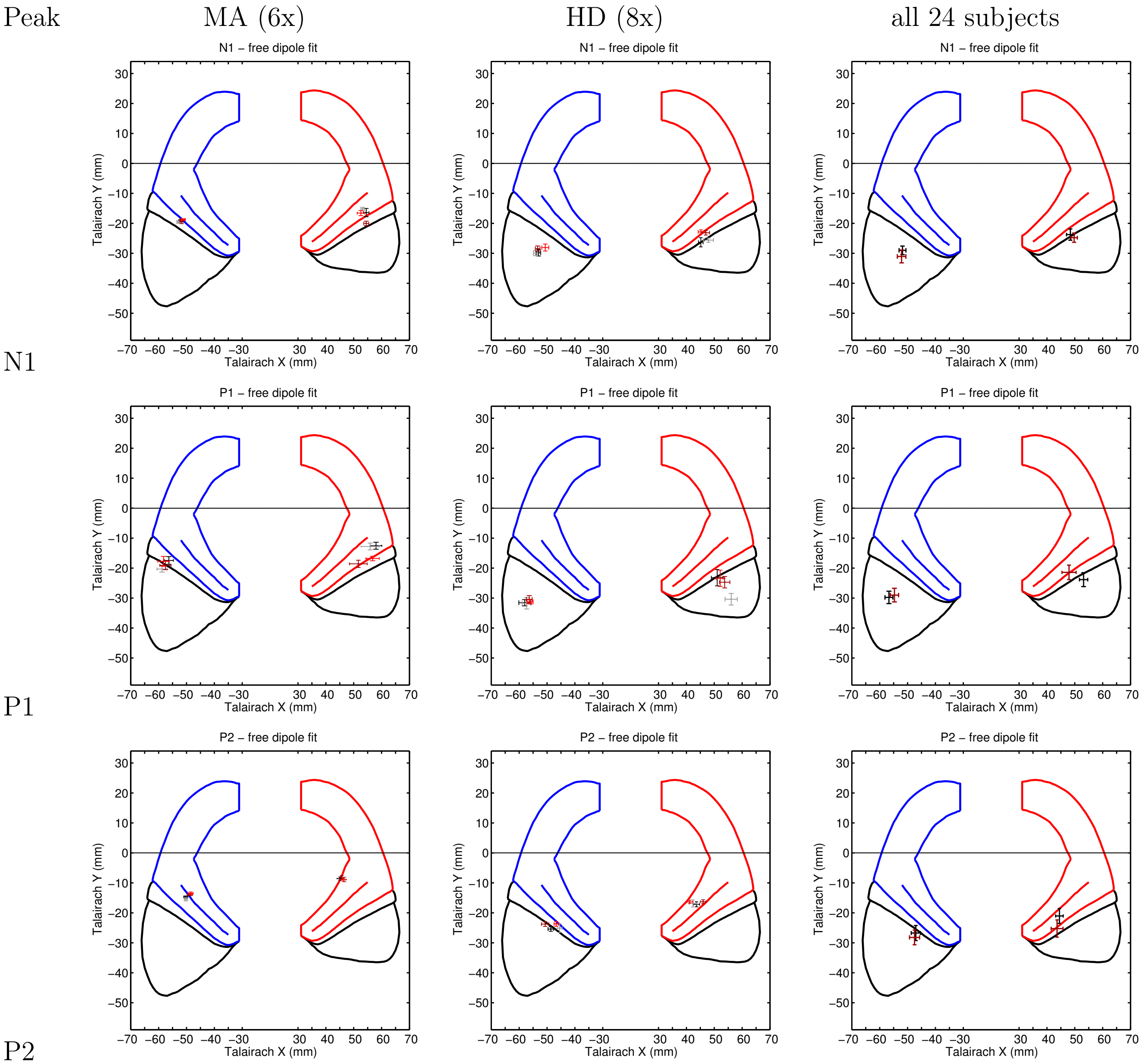


Figure A.3: Localization of Dipoles

(black = sinusoidal tone, red = Steinway tone, light colors = -10dB)

As can be seen in this figure, neither sort of stimuli nor sound level change the localizations of the 2-dipole model. The error bars of the localizations evolved from the standard error of mean.

A.0.3. Tables

For each measurement, a 2-dipole-model was adjusted freely with one dipole for each hemisphere.

Subject MA The N1 component of subject MA is consistently larger for the sinusoidal stimuli than for the Steinway stimuli. The P1 component of subject MA does not show big differences between neither stimuli nor loudness. Subject MA shows larger P2 components for the sinusoidal tone when it is reduced in intensity, while the P2 components of the piano tone does not depend on the sound intensity. Thus the difference between sinusoidal and piano tone does not remain the same.

	left dipole moment [nAm]				**right dipole moment [nAm]**			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
MA	-65.35	-65.85	-57.83	-58.01	-34.80	-37.97	-21.00	-35.73
MA	-64.76	-70.64	-67.49	-81.46	-31.32	-36.83	-29.95	-29.75
MA	-69.48	-72.85	-56.86	-60.78	-40.66	-36.56	-22.76	-20.77
MA	-69.53	-78.50	-77.40	-59.08	-48.03	-42.17	-27.61	-32.18
MA	-59.24	-66.61	-68.40	-72.08	-26.89	-40.49	-27.13	-36.30
MA	-68.66	-64.29	-57.20	-66.52	-38.66	-31.90	-26.41	-24.80
MEAN	-66.17	-69.79	-64.20	-66.32	-36.73	-37.65	-25.81	-29.92
Std-Err	1.62	2.18	3.40	3.72	3.04	1.46	1.35	2.51
Std-Dev	3.98	5.33	8.32	9.11	7.44	3.56	3.31	6.16

Table A.1: N1 components of the subject MA
For each measurement, a 2-dipole-model was adjusted freely with one dipole for each hemisphere. The N1 component of subject MA is consistently larger for the sinusoidal stimuli than for the Steinway stimuli. No effect of loudness can be noticed.

	left dipole moment [nAm]				right dipole moment [nAm]			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
MA	7.91	7.62	12.51	13.18	8.31	4.25	12.80	12.24
MA	14.18	6.48	9.98	9.94	11.64	12.02	9.39	7.34
MA	10.54	11.51	12.73	12.02	5.15	12.78	27.30	9.02
MA	10.48	7.54	16.96	18.56	5.35	11.06	10.93	13.87
MA	16.59	18.13	9.12	6.02	14.30	9.58	16.75	6.99
MA	6.50	8.59	4.49	7.61	9.06	3.30	11.88	9.97
MEAN	11.04	9.98	10.96	11.22	8.97	8.83	14.84	9.90
Std-Err	1.54	1.78	1.71	1.83	1.46	1.66	2.69	1.11
Std-Dev	3.78	4.35	4.19	4.47	3.57	4.07	6.59	2.72

Table A.2: P1 components of the subject MA

The P1 component of subject MA does not show big differences between neither stimuli nor loudness.

	left dipole moment [nAm]				right dipole moment [nAm]			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
MA	50.75	65.85	55.34	83.79	39.88	44.13	57.28	69.95
MA	64.96	83.15	80.79	58.02	50.82	62.82	63.05	57.94
MA	61.89	85.31	66.79	68.57	51.67	64.53	73.41	62.16
MA	79.97	101.53	87.51	82.11	56.42	73.72	80.52	76.48
MA	105.09	107.80	90.13	110.78	86.58	87.37	88.25	112.36
MA	92.41	94.65	103.40	97.93	70.78	76.06	67.96	79.06
MEAN	75.84	89.72	80.66	83.53	59.36	68.11	71.74	76.32
Std-Err	8.35	6.12	7.04	7.80	6.81	6.00	4.66	7.93
Std-Dev	20.44	14.98	17.25	19.11	16.69	14.71	11.42	19.42

Table A.3: P2 components of the subject MA

Subject MA shows larger P2 components of the sinusoidal tone when it is reduced in intensity, while the P2 components of the piano tone does not depend on the sound intensity.

Subject HD The P1 component of subject HD does not show big differences between neither stimuli nor loudness. The N1 component, however, is consistently larger for the piano than for the sinusoidal tone. The effect of loudness is smaller for the sinusoidal stimuli than for the Steinway piano tone. The P2 component of the piano stimulus is significantly larger for reduced sound intensity, while the sinusoidal stimulus does not shows such large differences concerning the sound intensity. The ratio of P2 components of sinusoidal to piano tone turns around when the sound is reduced.

	left dipole moment [nAm]				right dipole moment [nAm]			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
HD 1	-32.41	-31.64	-44.29	-66.23	-32.04	-16.49	-27.49	-44.19
HD 2	-31.42	-28.71	-36.88	-49.43	-33.65	-29.84	-45.29	-55.71
HD 3	-38.16	-26.13	-43.90	-69.56	-32.69	-20.92	-42.03	-60.99
HD 4	-25.91	-24.71	-40.46	-48.82	-28.53	-22.10	-29.37	-45.52
HD 5	-31.45	-38.47	-37.21	-41.43	-27.53	-33.06	-37.36	-43.94
HD 6	-29.77	-29.35	-33.24	-41.00	-29.91	-27.13	-36.64	-39.72
HD 7	-46.48	-35.38	-49.37	-57.82	-38.24	-33.31	-46.41	-55.74
HD 8	-37.53	-37.19	-39.84	-53.40	-31.17	-37.93	-40.3	-38.57
MEAN	-34.14	-31.45	-40.65	-53.46	-31.72	-27.6	-38.11	-48.05
Std-Err	2.25	1.81	1.80	3.73	1.18	2.58	2.44	2.94
Std-Dev	6.37	5.12	5.09	10.55	3.35	7.30	6.89	8.30

Table A.4: N1 components of the subject HD

The N1 component of subject HD is consistently larger for the piano than for the sinusoidal tone. The effect of loudness is smaller for the sinusoidal stimuli than for the Steinway piano tone.

	left dipole moment [nAm]				right dipole moment [nAm]			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
HD 1	22.41	7.08	9.39	14.01	13.54	3.32	4.69	5.74
HD 2	10.26	9.43	10.25	9.74	6.91	4.64	11.65	8.45
HD 3	7.07	10.25	13.56	11.36	11.02	4.35	11.86	10.02
HD 4	6.68	12.62	15.73	12.89	7.00	6.84	13.84	14.57
HD 5	5.72	7.14	10.07	19.34	9.78	8.20	14.09	13.57
HD 6	11.78	6.54	12.90	9.28	15.49	3.63	12.44	6.41
HD 7	10.87	6.37	17.41	12.75	13.13	8.87	16.95	9.56
HD 8	10.44	6.31	13.69	16.15	9.51	1.64	7.03	14.09
MEAN	10.65	8.22	12.87	13.19	10.80	5.19	11.57	10.30
Std-Err	1.85	0.82	1.01	1.18	1.10	0.90	1.40	1.22
Std-Dev	5.25	2.31	2.85	3.34	3.10	2.53	3.95	3.45

Table A.5: P1 components of the subject HD

The P1 component of subject HD does not show big differences between neither stimuli nor loudness.

	left dipole moment [nAm]				right dipole moment [nAm]			
subject	**sinld**	**sinsl10**	**stwld**	**stwsl10**	**sinld**	**sinsl10**	**stwld**	**stwsl10**
HD 1	34.15	49.68	34.33	51.20	44.69	38.36	41.57	61.94
HD 2	40.39	45.81	30.42	62.42	60.27	54.32	41.23	72.56
HD 3	47.92	50.57	40.60	76.61	45.47	32.95	37.87	91.63
HD 4	51.72	38.20	31.99	57.06	47.16	39.51	36.93	77.00
HD 5	47.29	28.37	25.44	73.78	62.77	36.06	41.13	104.39
HD 6	31.94	42.34	43.19	59.30	51.72	55.50	39.94	87.64
HD 7	50.75	55.77	52.72	79.44	65.26	69.75	63.32	117.51
HD 8	56.77	63.23	42.76	75.06	55.05	57.30	59.95	86.50
MEAN	45.11	46.75	37.68	66.86	54.05	47.97	45.24	87.40
Std-Err	3.11	3.80	3.10	3.75	2.85	4.61	3.64	6.25
Std-Dev	8.78	10.74	8.76	10.60	8.07	13.04	10.29	17.69

Table A.6: P2 components of the subject HD

The P2 component of the piano stimulus of subject HD is significantly larger for reduced sound intensity, while the sinusoidal stimulus does not shows such large differences concerning the sound intensity. The ratio of P2 components of sinusoidal to piano tone turns around when the sound is reduced.

B. Detailed Results of this Dissertation

In this section more details of the results from Sec. 4 will be presented. The tools of data analysis from Sec. 3.3 were applied on the MEG data, starting with a 2-dipole model, whose dipoles were adjustably freely for each measurement and fit with one dipole for each hemisphere. For each stimulus, 200 signals were averaged. The fitting intervals around the peaks were determined from baseline to baseline around each peak, which resulted in the following approximate fitting intervals: $\sim 50 \pm 20$ ms for P1, $\sim 110 \pm 20$ ms for N1, $\sim 250 \pm 30$ ms for P2, and $\sim 450 \pm 150$ ms for SF. For the data analysis, I evaluated all components, as well as the integrated sustained field (ISF) over the period of 300 to 1000 ms of the SF fit. The latter was done to exclude the influence of transient signals on the sustained field.

In the following tables the individual results are presented for the integrated sustained field (Tab. B.1 - Tab. B.8) as well as transient components such as P1 (Tab. B.9 - Tab. B.16), N1 (Tab. B.17 - Tab. B.24), P2 (Tab. B.25 - Tab. B.32) and the sustained fields' peaks (Tab. B.33 - Tab. B.40).

B.1. Integrated Sustained Fields

	left ISF [nAm · s]				right ISF [nAm · s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	-2.40	-6.40	-16.35	2.56	-5.20	-2.08	-3.65	3.76
VPN 2	-16.90	-8.08	-23.56	-11.19	-13.47	-21.23	-33.12	-24.09
VPN 3	-8.83	-8.02	-12.82	-5.12	-10.03	-7.18	-6.09	-5.99
VPN 4	-7.48	-14.06	-13.90	-6.79	-11.81	-11.33	-9.50	-5.22
VPN 5	-3.30	-2.91	-0.86	-0.52	-10.37	-3.97	-1.66	-1.22
VPN 6	-15.67	-13.74	-9.60	-9.66	-17.68	-7.42	-16.22	-1.82
VPN 7	-28.54	-25.96	-28.46	-27.81	-27.88	-15.01	-29.57	-14.63
VPN 8	-11.90	-2.18	-17.19	-11.02	-22.23	-5.13	-6.85	-4.39
VPN 9	-14.43	-21.56	-8.26	-7.51	-11.93	-21.36	-11.86	-8.43
VPN 10	-26.48	-9.22	-13.49	-5.27	-20.29	-17.43	-15.46	-10.21
VPN 11	-10.82	-7.18	-11.10	-6.02	-17.51	-8.59	-19.42	-5.86
VPN 12	-12.11	-9.73	-13.73	-11.38	-16.79	-7.35	-18.16	-12.07
VPN 13	-14.44	-10.02	-21.05	-4.22	-4.01	-3.27	-6.09	-1.78
VPN 14	-8.31	-4.11	-7.68	-8.02	-15.61	-8.11	-12.79	-4.01
VPN 15	-10.12	-22.57	-18.89	-4.52	-9.53	-23.34	-17.14	-8.82
VPN 16	-7.60	-7.85	-4.96	-4.93	-9.84	-5.11	-29.16	-7.49
VPN 17	-11.96	-5.43	-6.35	-0.09	-13.56	-13.15	-17.30	-4.09
VPN 18	-28.53	-21.22	-19.95	-14.99	-13.33	-18.56	-17.55	-19.46
VPN 19	-12.76	-15.05	-9.92	-5.29	-9.21	-11.60	-12.36	-6.61
VPN 20	-18.31	-17.82	-7.40	0.78	-6.44	-5.41	-10.55	-11.45
Mean	-13.54	-11.66	-13.28	-7.05	-13.34	-10.83	-14.73	-7.69
Std Dev	7.38	7.02	6.84	6.60	5.90	6.60	8.56	6.45
Std Err	1.65	1.57	1.53	1.48	1.32	1.48	1.91	1.44

Table B.1: Chinese integrated sustained fields for the syllable /ma/
In this table all individual integrated sustained fields of the Chinese subjects' both hemispheres for the syllable /ma/ with its four tones are represented.

	left ISF [nAm · s]				right ISF [nAm · s]			
subject	/mu1/	/mu2/	/mu3/	/mu4/	/mu1/	/mu2/	/mu3/	/mu4/
VPN 1	-7.07	-5.67	-13.59	-1.38	-3.68	-1.58	-6.67	-0.08
VPN 2	-12.22	-14.21	-16.54	-8.91	-17.16	-19.38	-20.85	-7.68
VPN 3	-13.12	-5.10	-12.38	-8.70	-5.25	-4.37	-7.37	-4.97
VPN 4	-18.05	-9.88	-11.37	-3.00	-11.42	-8.55	-10.61	-2.62
VPN 5	-7.11	-5.24	-6.07	-1.00	-7.12	-6.57	-6.89	-4.61
VPN 6	-11.60	-13.46	-13.09	-6.25	-7.16	-8.20	-13.61	-9.71
VPN 7	-14.56	-27.48	-47.13	-22.00	-18.18	-21.36	-33.33	-17.60
VPN 8	-19.19	-6.34	-19.52	-11.32	-15.12	-23.29	-22.23	-16.91
VPN 9	-9.60	-25.28	-18.20	-7.43	-12.74	-7.75	-12.40	-8.83
VPN 10	-14.58	-4.80	-8.08	-6.63	-15.72	-11.83	-12.42	-6.56
VPN 11	-9.99	-7.89	-12.35	-1.51	-10.29	-8.46	-9.00	-12.16
VPN 12	-8.75	-10.45	-9.58	-6.36	-10.55	-10.93	-26.86	-27.21
VPN 13	-9.21	-11.36	-14.37	-5.05	-2.10	-3.03	-4.70	-5.26
VPN 14	-13.85	-8.35	-5.34	-2.61	-7.86	-5.36	-8.37	-6.16
VPN 15	-5.72	-12.06	-8.70	-1.62	-10.33	-9.19	-12.59	-2.17
VPN 16	-8.85	-6.62	-5.92	-2.39	-5.56	-21.96	-7.33	-5.44
VPN 17	-4.89	-14.97	-14.24	-1.48	-15.14	-19.70	-19.09	-6.57
VPN 18	-17.82	-19.74	-14.94	-12.00	-10.43	-19.63	-19.02	-22.33
VPN 19	-7.13	-10.20	-18.82	-2.98	-11.08	-14.39	-12.14	-9.15
VPN 20	-5.48	-1.25	-10.86	1.27	-2.64	-6.87	-6.24	-3.34
Mean	-10.94	-11.02	-14.05	-5.57	-9.98	-11.62	-13.59	-8.97
Std Dev	4.35	6.79	8.84	5.32	4.78	6.89	7.68	7.03
Std Err	0.97	1.52	1.98	1.19	1.07	1.54	1.72	1.57

Table B.2: Chinese integrated sustained fields for the syllable /mu/
In this table all individual integrated sustained fields of the Chinese subjects' both hemispheres for the syllable /mu/ with its four tones are represented.

	left ISF [nAm · s]				right ISF [nAm · s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-3.94	-13.11	-10.13	-3.12	-3.59	-3.54	-1.97	-5.62
VPN 2	-10.90	-1.69	-3.40	-8.32	-7.04	-6.86	-9.10	-4.86
VPN 3	-6.66	-6.43	-17.44	0.01	-7.45	-13.56	-8.82	-2.83
VPN 4	-8.54	-6.79	-5.62	-2.96	-4.49	-2.39	-3.02	-3.31
VPN 5	-5.27	-5.54	-4.19	-1.07	-4.11	-7.93	-10.53	-2.00
VPN 6	-2.82	-8.14	-7.50	-9.37	-4.75	-4.45	-5.08	-7.33
VPN 7	-23.58	-25.25	-26.22	-17.31	-26.11	-27.24	-26.95	-16.63
VPN 8	-4.60	-11.66	-4.25	-0.46	-3.57	-16.13	-10.90	-6.35
VPN 9	-3.70	-9.87	-11.08	-1.87	-6.56	-11.42	-9.30	-7.57
VPN 10	-4.88	-4.28	-6.89	-7.29	-6.21	-7.44	-6.31	-8.49
VPN 11	-5.07	-3.58	-9.90	-5.91	-3.93	-6.08	-9.66	-4.96
VPN 12	-7.69	-7.61	-13.18	-3.38	-6.97	-13.47	-16.96	-14.61
VPN 13	0.37	-4.68	-3.16	3.10	0.60	2.43	7.86	-0.96
VPN 14	-3.23	-3.08	-4.67	-4.46	-2.91	-8.05	-4.56	-6.76
VPN 15	-0.06	-3.80	-1.04	-1.94	-1.04	-1.65	-4.00	-1.23
VPN 16	-6.30	-2.88	-3.39	-18.52	-6.96	-7.44	-4.70	-3.82
VPN 17	-4.39	-4.59	-4.84	2.58	-6.74	-10.41	-8.41	-6.05
VPN 18	-12.03	-26.94	-10.09	-0.59	-9.12	-12.50	-5.97	-5.80
VPN 19	-4.68	-16.34	-8.85	-5.78	-7.42	-8.03	-13.41	-6.71
VPN 20	-2.16	0.91	-3.55	3.61	-10.11	-0.15	-2.45	0.23
Mean	-6.01	-8.27	-7.97	-4.15	-6.42	-8.32	-7.71	-5.78
Std Dev	5.16	7.33	5.90	5.91	5.31	6.54	6.83	4.14
Std Err	1.15	1.64	1.32	1.32	1.19	1.46	1.53	0.93

Table B.3: Chinese integrated sustained fields for the vowel /o/

In this table all individual integrated sustained fields of the Chinese subjects' both hemispheres for the vowel /o/ with its four tones are represented.

	left ISF [nAm·s]				right ISF [nAm·s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	-5.81	-12.85	-2.87	5.04	-1.13	-5.44	0.46	-3.35
VPN 2	-8.41	-2.93	-1.24	-3.62	-9.14	-7.83	-7.72	-6.71
VPN 3	-9.15	-1.14	-4.84	-2.54	-10.79	-5.59	-8.45	-2.86
VPN 4	-11.14	-8.63	-17.47	-9.62	-3.91	-6.67	-17.49	-5.86
VPN 5	-0.96	-2.94	-6.39	-0.72	-1.40	-2.84	-18.43	-1.06
VPN 6	-7.30	-7.70	-11.74	-6.60	-4.82	-5.83	-7.86	-3.60
VPN 7	-24.23	-28.26	-27.92	-18.05	-14.13	-24.44	-23.24	-20.79
VPN 8	-6.56	-8.45	-16.51	0.87	-11.94	-9.70	-11.16	-0.88
VPN 9	-11.25	-17.29	-24.79	-5.62	-3.38	-9.19	-17.32	-3.46
VPN 10	-7.28	-1.83	-8.69	-3.00	-3.52	-2.95	-7.95	-0.48
VPN 11	-6.36	-3.11	-4.45	-1.64	-5.06	-3.51	-6.64	-2.86
VPN 12	-4.68	-4.39	-12.66	-7.09	-6.61	-7.41	-33.89	-12.24
VPN 13	-4.09	-9.41	-7.87	-1.51	-1.23	0.96	-0.59	-1.61
VPN 14	-4.04	-1.32	-1.89	0.42	-5.90	-6.33	-11.43	-1.07
VPN 15	-1.25	-4.22	-0.44	2.26	-1.43	-4.80	-1.25	-2.78
VPN 16	-11.98	-4.05	-4.45	-1.88	-14.05	-13.26	-5.11	-5.25
VPN 17	-5.74	-3.19	-6.46	-5.19	-7.21	-18.52	-7.61	-8.74
VPN 18	-17.88	-11.82	-14.56	-5.80	-4.98	-25.02	-21.03	-3.90
VPN 19	-1.35	-5.85	-18.36	-7.73	-5.64	-20.63	-19.63	-6.81
VPN 20	-11.22	-2.43	-0.87	9.84	-3.13	2.29	-1.99	3.69
Mean	-8.03	-7.09	-9.72	-3.11	-5.97	-8.84	-11.42	-4.53
Std Dev	5.65	6.60	8.03	5.79	4.09	7.74	8.89	5.11
Std Err	1.26	1.48	1.80	1.29	0.92	1.73	1.99	1.14

Table B.4: Chinese integrated sustained fields for the vowel /ö/
In this table all individual integrated sustained fields of the Chinese subjects' both hemispheres for the vowel /ö/ with its four tones are represented.

	left ISF [nAm · s]				**right ISF [nAm · s]**			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	6.82	1.85	15.25	0.27	13.91	27.73	21.10	0.92
VPN 2	-14.30	-8.22	-6.38	1.12	-6.46	-4.30	-2.86	-5.74
VPN 3	-7.61	-5.02	-3.38	-4.98	-4.46	-1.78	-4.21	-2.66
VPN 4	-16.98	-22.65	-29.23	-31.37	-8.14	-15.40	-23.85	-10.59
VPN 5	-8.48	-1.70	-3.80	-7.10	-12.04	-5.10	-9.02	-2.95
VPN 6	-2.61	1.94	-1.97	9.83	-1.57	0.97	0.07	3.72
VPN 7	2.23	3.59	0.98	17.93	2.88	1.69	3.63	9.89
VPN 8	-4.57	3.83	-15.27	1.52	-6.44	2.79	0.05	1.25
VPN 9	-10.17	-7.22	-11.53	-7.60	-11.66	-10.18	-10.37	-6.62
VPN 10	-0.60	3.69	-2.09	3.86	-3.58	2.29	-1.42	-2.11
VPN 11	-12.51	-5.26	-18.33	-6.79	-9.55	-6.50	-16.74	-10.17
VPN 12	-4.63	-0.20	-11.81	-4.32	-5.92	-1.36	-10.51	-1.89
VPN 13	-1.11	-1.15	-1.62	-2.79	-3.84	-2.50	-3.13	0.86
VPN 14	-17.91	-0.79	-6.19	-3.40	-12.00	-1.30	-2.80	-4.60
VPN 15	-18.05	-7.26	-14.60	-3.91	-14.21	-8.39	-9.70	-21.73
VPN 16	-6.77	-4.66	-5.45	-4.07	-7.57	-3.77	-4.05	-2.80
VPN 17	-5.59	-2.12	-2.86	-1.46	-11.02	-3.17	-5.42	-2.46
VPN 18	-10.18	-0.05	-5.63	-3.30	-4.81	-1.80	-5.13	-2.30
VPN 19	-2.11	-7.19	-17.58	-3.35	-6.13	-1.24	-17.88	-1.35
VPN 20	-5.61	-1.62	-7.45	1.87	-19.42	0.43	-12.04	-0.56
Mean	-7.04	-3.01	-7.45	-2.40	-6.60	-1.54	-5.71	-3.09
Std Dev	6.72	6.03	9.13	9.12	6.88	8.20	9.26	6.30
Std Err	1.50	1.35	2.04	2.04	1.54	1.83	2.07	1.41

Table B.5: German integrated sustained fields for the syllable /ma/
In this table all individual integrated sustained fields of the German subjects' both hemispheres for the syllable /ma/ with its four tones are represented.

	left ISF [nAm · s]				right ISF [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	0.70	3.02	4.33	-0.78	36.16	6.15	-5.74	6.30
VPN 2	-1.32	-7.04	-13.70	-4.28	-3.53	-3.68	-6.62	-3.21
VPN 3	-4.36	16.81	-5.84	-0.91	-6.61	3.64	-6.21	-3.15
VPN 4	-28.98	-22.29	-26.81	-19.52	-10.47	-15.21	-14.80	-7.06
VPN 5	-6.59	-3.55	-8.59	-9.07	-8.31	-7.94	-5.88	-12.60
VPN 6	-3.45	5.44	-4.28	-0.26	-0.34	-2.65	-0.88	0.71
VPN 7	3.15	27.46	3.09	2.81	2.49	32.61	9.29	18.36
VPN 8	-2.41	-4.73	-6.45	0.31	-3.04	-1.07	-10.20	0.87
VPN 9	-9.82	-18.25	-10.94	-13.34	-11.48	-8.76	-7.82	-15.42
VPN 10	-2.43	0.30	-1.40	0.07	-1.14	-4.33	-4.82	-3.12
VPN 11	-7.16	-8.75	-8.01	-6.39	-10.15	-11.26	-7.58	-9.97
VPN 12	-4.83	-3.05	-7.37	-3.35	-5.05	-3.25	-6.25	-6.65
VPN 13	-6.17	-2.45	-2.10	-1.04	0.21	-1.05	0.44	0.27
VPN 14	-22.32	-5.86	-14.59	-6.92	-11.74	-4.73	-13.11	-4.76
VPN 15	-15.78	-16.08	-26.97	-11.22	-14.62	-9.85	-19.26	-8.74
VPN 16	-17.31	-4.77	-10.72	-4.28	-18.14	-1.65	-9.42	-2.44
VPN 17	-3.77	-3.75	-4.37	-1.15	-6.86	-8.22	-4.73	-7.91
VPN 18	-6.39	-7.10	-5.10	-0.16	-2.23	-4.87	-4.02	13.16
VPN 19	-4.27	-1.50	-1.41	-2.11	-5.63	-2.39	-5.65	-2.37
VPN 20	-3.21	-3.06	-18.01	-2.07	-15.10	-1.32	-7.02	0.20
Mean	-7.34	-2.96	-8.46	-4.18	-4.78	-2.49	-6.51	-2.38
Std Dev	7.95	11.00	8.40	5.50	11.13	9.63	5.82	8.05
Std Err	1.78	2.46	1.88	1.23	2.49	2.15	1.30	1.80

Table B.6: German integrated sustained fields for the syllable /mu/
In this table all individual integrated sustained fields of the German subjects' both hemispheres for the syllable /mu/ with its four tones are represented.

	left ISF [nAm · s]				right ISF [nAm · s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-18.61	17.02	-4.53	2.91	18.86	1.50	14.06	31.46
VPN 2	-4.22	-1.25	-4.30	-6.81	-5.69	-0.68	-4.46	-2.94
VPN 3	-0.55	-3.13	-0.45	-1.64	-5.80	-1.42	-1.86	-2.21
VPN 4	-11.79	-15.40	-22.34	-14.24	-6.52	-5.67	-15.75	-7.89
VPN 5	-2.33	-4.68	-4.27	-8.05	-1.22	-0.81	-5.15	-9.71
VPN 6	0.02	14.52	9.71	13.37	-1.13	6.86	-1.63	3.04
VPN 7	-5.29	-8.70	2.92	1.68	-2.04	-0.47	14.98	4.76
VPN 8	-6.57	-1.62	-5.89	0.34	2.03	2.72	-3.61	1.59
VPN 9	-9.65	-5.60	-9.95	-7.89	-10.87	-6.25	-10.51	-5.73
VPN 10	0.74	0.03	-3.57	1.99	-0.91	-1.01	-0.74	0.24
VPN 11	-13.16	-10.11	-14.05	-15.76	-9.50	-11.30	-9.81	-8.87
VPN 12	-5.96	-1.12	-6.07	-2.48	-1.19	-1.99	-6.08	-0.29
VPN 13	-0.45	-2.27	-2.71	-2.62	0.57	-1.01	-3.20	-1.78
VPN 14	-21.79	-3.06	-22.75	-0.31	-11.10	-5.80	-10.95	-7.67
VPN 15	-6.21	-2.71	-9.82	-4.35	-11.82	-7.32	-9.34	-5.83
VPN 16	-4.17	-7.73	-11.29	-4.78	-3.86	-0.87	-6.33	-2.53
VPN 17	-3.42	-1.70	-12.48	0.14	-13.06	-3.68	-14.68	-8.55
VPN 18	-4.18	-1.36	-1.41	0.68	-2.64	1.73	-0.20	-12.47
VPN 19	1.59	-0.80	-3.92	-1.31	-0.76	-3.69	-5.29	-2.82
VPN 20	-8.05	-6.84	-2.70	-3.72	-4.57	-0.49	-0.41	0.14
Mean	-6.20	-2.33	-6.49	-2.64	-3.56	-1.98	-4.05	-1.90
Std Dev	6.24	7.29	7.70	6.29	6.92	4.00	7.79	9.10
Std Err	1.40	1.63	1.72	1.41	1.55	0.90	1.74	2.03

Table B.7: German integrated sustained fields for the vowel /o/
In this table all individual integrated sustained fields of the German subjects' both hemispheres for the vowel /o/ with its four tones are represented.

	left ISF [nAm · s]				**right ISF [nAm · s]**			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	7.40	7.18	26.54	1.04	17.51	2.18	6.76	9.34
VPN 2	-4.91	-4.37	-5.12	-4.04	-1.92	-9.40	-4.76	-1.62
VPN 3	-2.25	4.49	-0.09	-1.77	-2.12	-0.84	-0.48	-3.17
VPN 4	-13.64	-22.73	-12.84	-17.32	-7.37	-17.22	-7.44	-5.76
VPN 5	-8.16	-5.82	-3.34	-8.23	-10.45	-5.83	-2.38	-12.46
VPN 6	5.81	5.93	-1.56	0.94	3.76	7.82	-3.05	0.61
VPN 7	-4.98	15.61	1.16	7.26	-0.91	12.63	4.75	41.13
VPN 8	1.15	7.21	0.11	-1.14	2.93	-0.58	2.90	2.73
VPN 9	-14.06	-8.01	-10.57	-5.31	-10.45	-8.19	-8.34	-5.52
VPN 10	1.27	1.23	0.29	-1.38	3.98	-2.48	-0.90	-1.01
VPN 11	-16.32	-17.22	-10.40	-14.23	-11.96	-11.18	-12.66	-11.14
VPN 12	-8.61	-6.24	-8.11	-5.61	-2.20	-3.74	-11.55	-3.56
VPN 13	1.89	2.74	-1.02	-2.52	5.23	2.15	0.17	-0.04
VPN 14	-2.36	-22.01	-16.50	-1.65	-6.26	-12.18	-9.52	-7.00
VPN 15	-2.23	-9.13	-10.72	-5.47	-9.82	-7.61	-10.27	-5.74
VPN 16	-3.09	-2.26	-6.41	-9.32	-1.70	-3.52	-5.23	-5.13
VPN 17	-2.16	1.77	-2.51	-0.33	-7.74	-3.09	-7.14	-0.21
VPN 18	-2.02	8.61	-4.40	4.81	-1.46	-8.00	-5.03	3.57
VPN 19	1.91	-4.27	-2.40	0.00	-0.31	-3.26	-3.30	-1.93
VPN 20	-0.59	-3.00	-6.25	-1.54	-1.38	-7.31	-11.75	-1.60
Mean	-3.30	-2.51	-3.71	-3.29	-2.13	-3.98	-4.46	-0.43
Std Dev	6.30	10.08	8.65	5.81	6.93	6.89	5.55	10.95
Std Err	1.41	2.25	1.93	1.30	1.55	1.54	1.24	2.45

Table B.8: German integrated sustained fields for the vowel /ö/
In this table all individual integrated sustained fields of the German subjects' both hemispheres for the vowel /ö/ with its four tones are represented.

B.2. Components

P1 The P1 fit was performed individually from baseline to baseline around the first positive peak at $\sim 50 \pm 20$ ms after tone onset for each subject.

	left P1 [nAm·s]				right P1 [nAm·s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	16	32	13	29	3	12	1	0
VPN 2	10	6	1	6	5	10	8	4
VPN 3	25	13	29	29	12	11	6	14
VPN 4	22	31	9	13	18	18	15	16
VPN 5	8	2	2	2	1	3	2	1
VPN 6	27	29	14	32	23	24	18	32
VPN 7	9	15	8	13	2	11	7	7
VPN 8	18	17	25	10	20	10	8	21
VPN 9	8	11	7	17	2	10	6	8
VPN 10	10	26	14	3	10	11	6	5
VPN 11	15	16	14	10	11	12	20	3
VPN 12	11	13	13	10	10	8	8	6
VPN 13	29	7	3	8	7	2	2	7
VPN 14	10	15	4	5	10	12	4	5
VPN 15	11	14	8	14	6	8	7	8
VPN 16	8	10	13	7	10	16	4	11
VPN 17	16	7	8	20	12	5	13	8
VPN 18	13	11	16	8	13	10	9	11
VPN 19	7	10	9	7	7	24	9	4
VPN 20	13	7	17	11	16	13	13	28
Mean	14.3	14.6	11.4	12.7	9.9	11.5	8.3	10.0
Std Dev	6.7	8.6	7.1	8.7	6.1	5.7	5.2	8.5
Std Err	1.5	1.9	1.6	1.9	1.4	1.3	1.2	1.9

Table B.9: P1 component of Chinese subjects for the syllable /ma/

	left P1 [nAm · s]				right P1 [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	19	15	19	39	2	1	0	15
VPN 2	11	10	3	6	21	5	11	8
VPN 3	26	12	45	33	4	7	20	13
VPN 4	15	12	18	20	12	14	13	21
VPN 5	2	2	4	7	5	4	3	4
VPN 6	21	22	19	25	19	17	18	16
VPN 7	17	4	6	11	17	15	4	22
VPN 8	16	20	23	24	6	17	19	29
VPN 9	12	7	3	15	13	5	6	9
VPN 10	7	2	6	5	6	15	8	9
VPN 11	14	16	3	7	2	21	1	5
VPN 12	9	7	12	10	6	6	13	4
VPN 13	11	7	14	11	9	10	10	7
VPN 14	10	7	10	37	14	8	12	14
VPN 15	10	7	17	11	9	1	10	7
VPN 16	8	20	5	13	8	6	6	9
VPN 17	9	13	6	14	9	10	8	17
VPN 18	9	14	15	9	9	11	13	9
VPN 19	11	18	10	14	13	7	8	4
VPN 20	6	12	13	18	13	10	15	18
Mean	12.2	11.4	12.6	16.5	9.9	9.5	9.9	12.0
Std Dev	5.6	6.0	9.9	10.2	5.3	5.5	5.7	6.9
Std Err	1.3	1.3	2.2	2.3	1.2	1.2	1.3	1.5

Table B.10: P1 component of Chinese subjects for the syllable /mu/

	left P1 [nAm · s]				right P1 [nAm · s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	16	15	20	20	0	5	0	8
VPN 2	3	6	10	16	8	3	8	10
VPN 3	7	27	8	5	7	12	9	11
VPN 4	24	28	26	27	19	19	21	15
VPN 5	8	13	8	3	15	11	8	3
VPN 6	21	28	18	25	24	29	18	22
VPN 7	18	15	16	12	19	7	10	5
VPN 8	18	16	15	23	12	13	8	13
VPN 9	19	11	14	16	18	10	14	7
VPN 10	2	2	4	2	6	3	6	5
VPN 11	12	19	13	15	15	7	21	21
VPN 12	12	13	14	11	7	4	4	6
VPN 13	9	7	5	2	6	21	8	4
VPN 14	14	3	4	11	7	4	8	7
VPN 15	17	10	15	8	10	6	12	5
VPN 16	10	8	16	18	11	9	13	9
VPN 17	5	10	14	10	6	9	14	6
VPN 18	9	9	14	6	6	11	15	12
VPN 19	12	14	8	17	4	4	12	15
VPN 20	24	12	11	-3	11	24	24	8
Mean	13.0	13.3	12.7	12.2	10.6	10.6	11.7	9.6
Std Dev	6.5	7.5	5.5	8.3	6.1	7.4	6.0	5.4
Std Err	1.5	1.7	1.2	1.8	1.4	1.7	1.4	1.2

Table B.11: P1 component of Chinese subjects for the vowel /o/

	left P1 [nAm · s]				right P1 [nAm · s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	17	11	15	23	0	1	0	7
VPN 2	11	3	10	5	13	7	11	11
VPN 3	14	10	18	2	6	11	9	5
VPN 4	18	19	25	25	11	12	19	13
VPN 5	6	4	9	11	4	1	12	11
VPN 6	21	25	22	17	14	22	24	21
VPN 7	13	9	15	10	23	10	26	12
VPN 8	33	10	13	14	6	16	24	8
VPN 9	10	13	13	8	5	17	7	9
VPN 10	8	5	2	7	10	3	5	5
VPN 11	16	7	17	7	11	5	9	7
VPN 12	12	8	11	10	9	7	7	3
VPN 13	9	7	7	14	5	5	8	9
VPN 14	6	3	8	4	12	9	13	8
VPN 15	10	15	12	15	6	7	7	18
VPN 16	9	13	3	6	8	10	5	6
VPN 17	13	10	7	29	15	8	10	19
VPN 18	8	12	9	21	9	11	9	12
VPN 19	7	18	8	16	8	6	4	6
VPN 20	56	21	13	4	13	27	23	17
Mean	14.9	11.2	11.9	12.4	9.4	9.8	11.6	10.4
Std Dev	11.5	6.0	5.8	7.6	5.0	6.6	7.5	5.1
Std Err	2.6	1.4	1.3	1.7	1.1	1.5	1.7	1.1

Table B.12: P1 component of Chinese subjects for the vowel /ö/

	left P1 [nAm · s]				right P1 [nAm · s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	9	8	7	14	18	14	9	9
VPN 2	29	26	22	31	21	6	8	21
VPN 3	10	14	7	3	16	23	7	13
VPN 4	8	12	8	21	2	8	6	28
VPN 5	10	8	17	9	14	17	11	24
VPN 6	20	14	35	20	15	31	27	14
VPN 7	23	30	80	42	17	19	57	51
VPN 8	20	10	18	26	16	14	11	9
VPN 9	13	6	2	11	12	5	3	13
VPN 10	11	16	5	29	10	6	10	19
VPN 11	11	2	3	7	12	5	7	6
VPN 12	13	14	10	44	13	7	4	6
VPN 13	15	15	15	18	12	7	17	13
VPN 14	7	22	36	5	4	9	10	8
VPN 15	14	19	24	25	11	15	11	16
VPN 16	9	8	7	11	7	2	5	6
VPN 17	26	25	41	40	22	16	54	56
VPN 18	24	8	16	15	4	10	6	29
VPN 19	11	8	11	8	11	11	15	8
VPN 20	17	18	12	22	14	14	8	11
Mean	15.0	14.2	18.8	20.1	12.6	12.0	14.3	18.0
Std Dev	6.5	7.4	18.2	12.4	5.4	7.0	15.1	14.0
Std Err	1.5	1.7	4.1	2.8	1.2	1.6	3.4	3.1

Table B.13: P1 component of German subjects for the vowel /ma/

	left P1 [nAm · s]				right P1 [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	15	15	13	9	8	8	8	19
VPN 2	23	19	24	36	8	8	18	18
VPN 3	22	17	16	19	21	26	21	8
VPN 4	27	8	11	20	22	0	4	4
VPN 5	7	14	4	12	18	19	6	27
VPN 6	28	17	28	20	32	15	23	29
VPN 7	42	62	41	49	19	36	19	37
VPN 8	28	11	17	18	18	7	12	14
VPN 9	4	4	10	12	13	6	3	13
VPN 10	18	21	7	19	9	3	4	23
VPN 11	2	14	3	5	8	2	1	5
VPN 12	21	8	5	12	10	12	2	3
VPN 13	8	4	13	10	10	5	4	4
VPN 14	6	16	4	20	6	8	6	8
VPN 15	20	31	26	34	21	22	16	22
VPN 16	12	17	21	17	7	5	19	9
VPN 17	36	23	31	42	43	23	38	50
VPN 18	13	11	20	14	12	6	10	7
VPN 19	25	18	14	11	6	4	4	3
VPN 20	19	19	14	20	9	7	7	11
Mean	18.8	17.5	16.1	20.0	15.0	11.1	11.3	15.7
Std Dev	10.7	12.3	10.1	11.6	9.6	9.4	9.4	12.6
Std Err	2.4	2.7	2.3	2.6	2.1	2.1	2.1	2.8

Table B.14: P1 component of German subjects for the vowel /mu/

	left P1 [nAm·s]				right P1 [nAm·s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	16	37	13	9	26	12	8	13
VPN 2	25	23	28	26	13	14	13	16
VPN 3	16	8	15	17	19	18	13	17
VPN 4	18	18	35	19	20	10	16	27
VPN 5	19	7	16	8	33	25	25	5
VPN 6	24	23	14	35	20	24	31	27
VPN 7	40	36	34	37	34	53	28	33
VPN 8	33	11	25	24	12	8	8	4
VPN 9	8	6	4	11	6	8	5	10
VPN 10	16	26	22	26	4	6	10	6
VPN 11	24	4	2	4	14	9	2	6
VPN 12	3	16	16	35	5	13	11	5
VPN 13	11	7	22	15	16	0	20	6
VPN 14	6	15	5	5	4	3	6	4
VPN 15	21	24	17	18	18	13	26	21
VPN 16	6	11	12	7	7	12	18	6
VPN 17	22	31	18	23	20	15	17	18
VPN 18	25	18	11	11	12	10	12	14
VPN 19	13	23	14	23	4	19	14	2
VPN 20	14	15	14	8	5	26	10	2
Mean	18.0	18.0	16.9	18.1	14.6	14.9	14.7	12.1
Std Dev	9.2	9.8	8.9	10.3	9.3	11.3	8.0	9.3
Std Err	2.1	2.2	2.0	2.3	2.1	2.5	1.8	2.1

Table B.15: P1 component of German subjects for the vowel /o/

	left P1 [nAm · s]				**right P1 [nAm · s]**			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	20	16	17	6	10	22	12	16
VPN 2	16	29	28	28	12	16	22	9
VPN 3	10	7	5	2	16	14	14	15
VPN 4	17	12	13	17	4	2	9	6
VPN 5	12	9	22	8	21	14	37	10
VPN 6	41	24	35	22	42	28	42	15
VPN 7	66	41	45	37	51	26	53	75
VPN 8	9	24	14	13	11	14	21	20
VPN 9	7	2	6	8	9	4	8	7
VPN 10	26	31	17	32	15	11	16	4
VPN 11	13	12	18	12	13	9	13	13
VPN 12	14	22	7	13	10	11	11	31
VPN 13	15	19	16	12	9	12	14	7
VPN 14	10	5	6	31	4	5	4	8
VPN 15	19	28	24	39	23	22	18	22
VPN 16	11	22	13	19	10	15	12	6
VPN 17	28	52	22	23	10	31	19	35
VPN 18	12	24	18	25	23	3	4	8
VPN 19	16	25	31	15	14	9	14	9
VPN 20	8	13	16	15	12	8	21	4
Mean	18.5	20.9	18.7	18.9	16.0	13.8	18.2	16.0
Std Dev	13.8	12.2	10.3	10.5	11.8	8.3	12.5	16.3
Std Err	3.1	2.7	2.3	2.3	2.6	1.9	2.8	3.6

Table B.16: P1 component of German subjects for the vowel /ö/

N1 The N1 fit was performed individually from baseline to baseline around the first negative peak at $\sim 110 \pm 20$ ms after tone onset for each subject.

	left N1 [nAm·s]				right N1 [nAm·s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	1	0	-1	-1	-10	-1	-8	-13
VPN 2	-26	-23	-21	-25	-35	-31	-17	-36
VPN 3	0	-19	-7	-31	-3	-35	-12	-29
VPN 4	-5	-12	-13	-22	-7	-9	-15	-17
VPN 5	-12	-11	-18	-11	-30	-13	-15	-15
VPN 6	-15	-20	-18	-7	-43	-16	-12	-11
VPN 7	-17	-21	-5	-9	-5	-3	-8	-2
VPN 8	-14	1	-15	-16	-22	-2	0	-21
VPN 9	-53	-64	-61	-38	-46	-40	-61	-19
VPN 10	-1	-14	-5	-8	-6	-21	-12	-10
VPN 11	-30	-17	-44	-20	-28	-35	-39	-41
VPN 12	-5	-5	-7	-6	-11	-17	-9	-18
VPN 13	-30	-15	-14	-15	-27	-9	-11	-7
VPN 14	-7	-3	-18	-37	-17	-9	-13	-13
VPN 15	-34	-41	-41	-41	-24	-15	-21	-27
VPN 16	-4	-14	-12	-8	-12	-5	-17	-4
VPN 17	-11	-16	-7	-10	-31	-44	-27	-28
VPN 18	-19	-15	-16	-22	-36	-30	-26	-36
VPN 19	-18	-36	-35	-32	-13	-15	-32	-12
VPN 20	-21	-9	-6	-7	-37	-15	-23	-13
Mean	-16.1	-17.7	-18.2	-18.3	-22.2	-18.3	-18.9	-18.6
Std Dev	13.6	15.1	15.5	12.2	13.4	13.2	13.5	11.0
Std Err	3.0	3.4	3.5	2.7	3.0	2.9	3.0	2.5

Table B.17: N1 component of Chinese subjects for the vowel /ma/

	left N1 [nAm · s]				right N1 [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	4	-13	-27	2	3	-7	-9	1
VPN 2	-64	-43	-43	-31	-27	-29	-28	-25
VPN 3	-27	-5	-8	-22	-35	-15	-4	-28
VPN 4	-14	-16	-34	-9	-11	-11	-17	-12
VPN 5	-17	-27	-33	-13	-16	-19	-32	-16
VPN 6	-8	-17	-16	-25	-5	-19	-22	-15
VPN 7	-13	-22	-27	-25	-4	-10	-7	-12
VPN 8	-23	-15	-11	-9	-14	-18	-10	-12
VPN 9	-41	-44	-50	-43	-27	-27	-31	-25
VPN 10	-8	-10	-8	-7	-11	-8	-1	-8
VPN 11	-25	-19	-23	-12	-36	-27	-13	-27
VPN 12	-10	-17	-3	-7	-16	-10	-10	-20
VPN 13	1	-14	-11	-15	-9	-9	-18	-6
VPN 14	-21	-29	-10	-3	-3	-13	-13	-9
VPN 15	-23	-17	-24	-26	-12	-15	-8	-17
VPN 16	-22	-10	-9	-14	-18	-12	-14	-15
VPN 17	-12	-19	-25	-12	-36	-33	-31	-35
VPN 18	-19	-13	-15	-23	-31	-30	-31	-39
VPN 19	-16	-12	-31	-26	-8	-9	-6	-7
VPN 20	-10	-10	-10	-27	-24	-20	-28	-24
Mean	-18.4	-18.6	-20.9	-17.4	-17.0	-17.1	-16.7	-17.6
Std Dev	14.7	10.2	12.9	11.0	11.8	8.2	10.3	10.2
Std Err	3.3	2.3	2.9	2.5	2.6	1.8	2.3	2.3

Table B.18: N1 component of Chinese subjects for the vowel /mu/

	left N1 [nAm · s]				right N1 [nAm · s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-8	-12	-14	-4	-14	-7	-16	-4
VPN 2	-11	-18	-42	-22	-14	-19	-38	-19
VPN 3	-11	-32	-24	-14	-21	-43	-30	-20
VPN 4	-12	-1	-17	-16	-24	-15	-14	-13
VPN 5	-27	-14	-23	-10	-13	-16	-20	-12
VPN 6	-11	-16	-25	-9	-15	-32	-19	-16
VPN 7	-5	0	-17	-24	-3	-1	-13	-14
VPN 8	-4	0	-14	-9	5	-1	-9	1
VPN 9	-48	-62	-62	-36	-26	-41	-47	-22
VPN 10	-3	-5	-8	-7	0	-6	-11	0
VPN 11	-29	-27	-35	-28	-24	-26	-39	-25
VPN 12	-16	-5	-13	-6	-18	-10	-14	-9
VPN 13	-13	-19	-20	-26	-6	-10	-18	-11
VPN 14	-14	-4	-13	-7	-2	-19	0	-7
VPN 15	-28	-23	-20	-28	-20	-14	-8	-31
VPN 16	-5	-13	-15	-6	-6	-10	-12	-14
VPN 17	0	-8	-14	-6	-16	-26	-36	-26
VPN 18	-13	-23	-24	-25	-30	-27	-33	-22
VPN 19	-17	-19	-29	-10	-10	-3	-42	-8
VPN 20	-17	-22	-48	-21	-32	-22	-40	-23
Mean	-14.6	-16.2	-23.9	-15.7	-14.5	-17.4	-23.0	-14.8
Std Dev	11.3	14.3	13.6	9.7	10.2	12.3	13.8	8.8
Std Err	2.5	3.2	3.0	2.2	2.3	2.7	3.1	2.0

Table B.19: N1 component of Chinese subjects for the vowel /o/

	left N1 [nAm·s]				right N1 [nAm·s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	-4	-5	-7	11	-6	-10	-10	-1
VPN 2	-17	-33	-45	-26	-28	-31	-47	-32
VPN 3	-21	-30	-36	-21	-27	-36	-37	-27
VPN 4	-11	-21	-27	-7	0	-17	-11	-12
VPN 5	-8	-17	-12	-8	-9	-21	-18	-18
VPN 6	-18	-18	-21	-11	-28	-21	-30	-14
VPN 7	-5	-1	-1	-1	-2	-3	-4	0
VPN 8	2	-10	-12	2	-3	6	-27	13
VPN 9	-43	-35	-41	-45	-27	-23	-33	-24
VPN 10	-4	-12	-15	-30	-3	-9	-12	-11
VPN 11	-39	-47	-55	-43	-39	-54	-71	-62
VPN 12	-11	-7	-29	-7	-4	-11	-33	-10
VPN 13	-34	-18	-26	-14	-23	-15	-6	-5
VPN 14	-5	-10	-10	-13	-11	-16	-25	-6
VPN 15	-26	-28	-30	-22	-18	-15	-24	-18
VPN 16	-5	-8	-7	-4	-5	-13	-13	-13
VPN 17	-9	-27	-41	-10	-25	-47	-58	-32
VPN 18	-26	-16	-25	-33	-35	-33	-35	-38
VPN 19	-20	-19	-21	-23	-24	-17	-20	-12
VPN 20	-14	-24	-26	-25	-28	-32	-36	-40
Mean	-15.9	-19.3	-24.4	-16.5	-17.3	-20.9	-27.5	-18.1
Std Dev	12.5	11.6	14.3	14.6	12.5	14.5	17.3	16.9
Std Err	2.8	2.6	3.2	3.3	2.8	3.2	3.9	3.8

Table B.20: N1 component of Chinese subjects for the vowel /ö/

	left N1 [nAm · s]				right N1 [nAm · s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	-44	-41	-31	-34	-26	-12	-24	-18
VPN 2	-38	-27	-20	-22	-18	-32	-39	-25
VPN 3	-21	-21	-18	-42	-5	-20	-5	-31
VPN 4	-29	-21	-19	-21	-11	-14	-8	-5
VPN 5	-25	-14	-3	-18	-8	-25	-10	-23
VPN 6	-4	-14	4	-16	-14	-1	13	-9
VPN 7	-25	-11	21	-20	-24	-34	4	-7
VPN 8	-17	-10	-18	-14	-14	-5	-10	-15
VPN 9	-15	-9	-6	-10	-13	-8	-15	-10
VPN 10	4	2	1	12	-5	1	-4	7
VPN 11	-24	-12	-8	-14	-49	-32	-15	-32
VPN 12	3	-19	-7	-31	-15	-27	-18	-13
VPN 13	-41	-44	-63	-57	-54	-59	-61	-47
VPN 14	-31	-8	0	-3	-21	-19	-8	-9
VPN 15	-27	-14	-16	-9	-38	-15	-24	-12
VPN 16	-28	-19	-15	-23	-33	-22	-26	-24
VPN 17	8	3	21	16	12	8	23	6
VPN 18	-21	-24	-11	-33	-16	-16	-21	-20
VPN 19	-49	-30	-14	-28	-52	-28	-17	-28
VPN 20	-33	-30	-22	-26	-38	-35	-13	-27
Mean	-22.9	-18.2	-11.2	-19.7	-22.1	-19.8	-13.9	-17.1
Std Dev	15.8	12.2	18.0	16.8	17.3	15.3	17.7	13.1
Std Err	3.5	2.7	4.0	3.8	3.9	3.4	4.0	2.9

Table B.21: N1 component of German subjects for the vowel /ma/

	left N1 [nAm·s]				right N1 [nAm·s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	-30	-37	-33	-51	-27	-33	-27	-44
VPN 2	-21	-22	-23	-33	-35	-19	-15	-38
VPN 3	-30	-22	-15	-15	-14	-18	-43	-22
VPN 4	-28	-19	-28	-21	-6	-14	-19	-11
VPN 5	-20	-7	-12	2	-26	-20	-18	-18
VPN 6	-7	-11	-16	-14	-5	-17	-22	-9
VPN 7	-11	-3	-11	-14	-10	-18	-15	-9
VPN 8	-21	-15	-23	-13	-10	-16	-24	-15
VPN 9	-11	-19	-9	-12	-12	-10	-13	-12
VPN 10	0	-3	2	3	-11	-6	-8	-6
VPN 11	-42	-14	-1	-27	-38	-36	-23	-38
VPN 12	-14	-19	-14	-13	-28	-26	-28	-20
VPN 13	-34	-19	-36	-38	-36	-25	-37	-41
VPN 14	-21	-30	-7	-12	-12	-19	-20	-11
VPN 15	-30	-18	-22	-28	-33	-18	-23	-36
VPN 16	-22	-18	-14	-19	-28	-20	-21	-26
VPN 17	3	1	3	2	0	3	0	7
VPN 18	-40	-30	-13	-33	-7	-4	-4	-15
VPN 19	-36	-43	-31	-39	-25	-31	-15	-26
VPN 20	-27	-38	-30	-30	-12	-16	-15	-17
Mean	-22.1	-19.3	-16.7	-20.3	-18.8	-18.2	-19.5	-20.4
Std Dev	12.5	11.9	11.4	14.5	11.9	9.5	10.0	13.5
Std Err	2.8	2.7	2.6	3.3	2.7	2.1	2.2	3.0

Table B.22: N1 component of German subjects for the vowel /mu/

	left N1 [nAm·s]				right N1 [nAm·s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-34	-21	-38	-25	-18	-20	-17	-17
VPN 2	-27	-19	-28	-17	-19	-12	-17	-47
VPN 3	-9	-11	-33	-19	-10	-17	-17	-8
VPN 4	-19	-24	-27	-19	-16	-13	-17	-14
VPN 5	-20	-5	-19	-6	-38	-13	-14	-27
VPN 6	-4	-16	-17	-7	-12	-15	-13	-17
VPN 7	-22	-17	-13	-11	-29	-28	-27	-7
VPN 8	-19	-25	-34	-14	-15	-5	-8	-11
VPN 9	-7	-9	-30	-6	-11	-16	-36	-20
VPN 10	8	5	1	6	-2	-23	-8	-3
VPN 11	-8	-18	-26	-48	-22	-37	-51	-52
VPN 12	-11	-23	-16	-4	-38	-23	-35	-18
VPN 13	-27	-20	-35	-20	-47	-30	-23	-20
VPN 14	-10	-23	-23	-6	-7	-23	-16	0
VPN 15	-15	-27	-37	-23	-24	-37	-41	-26
VPN 16	-22	-28	-33	-9	-32	-23	-21	-18
VPN 17	-4	-5	-10	-6	-17	1	-28	-19
VPN 18	-29	-46	-41	-26	-6	-16	-14	-11
VPN 19	-34	-36	-28	-41	-29	-41	-26	-42
VPN 20	-16	-40	-39	-31	-41	-33	-43	-33
Mean	-16.5	-20.4	-26.3	-16.6	-21.7	-21.2	-23.6	-20.5
Std Dev	11.0	12.2	11.0	13.2	12.7	10.9	12.1	14.0
Std Err	2.5	2.7	2.5	3.0	2.8	2.4	2.7	3.1

Table B.23: N1 component of German subjects for the vowel /o/

	left N1 [nAm·s]				right N1 [nAm·s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	-37	-37	-42	-49	-22	-59	-49	-54
VPN 2	-31	-18	-36	-27	-25	-45	-32	-30
VPN 3	-11	-22	-27	-23	-6	-14	-17	-4
VPN 4	-13	-26	-30	-16	-11	-11	-13	-11
VPN 5	-14	-25	-39	-7	-18	-18	-16	-4
VPN 6	-2	-11	-11	-11	-9	-9	-10	-14
VPN 7	-5	-13	-16	-7	-28	-18	-30	-15
VPN 8	-13	-42	-34	-14	-26	-22	-12	-22
VPN 9	-17	-18	-24	-22	-19	-26	-34	-21
VPN 10	6	6	2	13	-3	-4	-32	-8
VPN 11	-20	-16	-26	-19	-42	-44	-54	-30
VPN 12	-4	-15	-23	-12	-19	-25	-44	-33
VPN 13	-29	-48	-47	-33	-41	-55	-55	-44
VPN 14	-11	-23	-43	-7	-4	-17	-22	-11
VPN 15	-24	-35	-37	-21	-27	-33	-42	-32
VPN 16	-25	-23	-15	-17	-20	-28	-22	-26
VPN 17	2	-3	-15	5	11	-16	-24	11
VPN 18	-48	-42	-44	-42	-8	-13	-17	-23
VPN 19	-34	-58	-39	-35	-20	-33	-30	-22
VPN 20	-45	-40	-54	-33	-57	-39	-54	-26
Mean	-18.8	-25.5	-30.0	-18.9	-19.7	-26.5	-30.5	-21.0
Std Dev	15.2	15.8	14.1	15.1	15.4	15.4	14.9	14.8
Std Err	3.4	3.5	3.2	3.4	3.5	3.4	3.3	3.3

Table B.24: N1 component of German subjects for the vowel /ö/

P2 The P2 fit was performed individually from baseline to baseline around the second positive peak, which was at $\sim 250 \pm 30$ ms after tone onset for each subject.

	left P2 [nAm·s]				right P2 [nAm·s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	46	14	14	-7	35	5	3	-3
VPN 2	-2	-4	-12	-2	0	2	-3	-3
VPN 3	18	21	41	54	6	17	20	25
VPN 4	9	-8	0	-3	7	-3	-1	-12
VPN 5	25	29	23	20	31	25	16	23
VPN 6	18	15	7	19	22	3	8	22
VPN 7	-5	1	-2	0	7	6	6	12
VPN 8	13	17	13	22	19	32	19	29
VPN 9	20	9	23	10	10	1	16	1
VPN 10	21	17	16	17	11	11	-7	18
VPN 11	25	38	42	38	11	21	29	22
VPN 12	-3	13	-1	-1	-10	8	-2	-3
VPN 13	18	9	18	18	35	10	15	17
VPN 14	1	-2	2	-6	5	12	-10	11
VPN 15	2	8	1	1	-12	-5	-10	-16
VPN 16	10	25	9	7	25	36	14	16
VPN 17	39	18	18	36	17	18	14	38
VPN 18	32	17	16	17	29	20	18	15
VPN 19	18	27	11	13	18	10	4	9
VPN 20	44	16	15	25	41	24	35	36
Mean	17.5	14.0	12.7	13.9	15.4	12.7	9.2	12.9
Std Dev	15.0	11.5	13.4	16.2	14.6	11.3	12.5	15.0
Std Err	3.4	2.6	3.0	3.6	3.3	2.5	2.8	3.4

Table B.25: P2 component of Chinese subjects for the vowel /ma/

	left P2 [nAm · s]				right P2 [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	18	1	1	20	14	15	13	14
VPN 2	-2	-8	-48	-4	5	-2	-57	4
VPN 3	19	28	20	46	29	12	-3	15
VPN 4	-2	-5	-9	3	-6	-3	-8	-2
VPN 5	19	15	2	22	19	14	6	29
VPN 6	19	15	8	16	15	18	12	30
VPN 7	5	-3	-51	1	3	0	-30	8
VPN 8	10	12	-9	13	18	12	3	18
VPN 9	11	9	4	-5	9	20	11	-4
VPN 10	16	21	13	24	7	-4	9	8
VPN 11	28	19	36	20	21	21	9	12
VPN 12	10	7	-5	-2	13	9	-6	-10
VPN 13	13	5	0	40	16	9	9	32
VPN 14	10	1	-4	16	6	7	-2	18
VPN 15	43	5	-3	21	-7	-11	-11	-6
VPN 16	11	11	-9	0	20	11	11	3
VPN 17	28	18	-9	26	8	13	1	23
VPN 18	18	9	11	22	17	15	17	14
VPN 19	16	2	-1	14	13	1	-4	9
VPN 20	6	9	4	21	23	23	21	39
Mean	14.8	8.6	-2.5	15.7	12.2	9.0	0.1	12.7
Std Dev	10.4	9.2	19.5	13.8	9.2	9.3	17.7	13.4
Std Err	2.3	2.1	4.4	3.1	2.0	2.1	4.0	3.0

Table B.26: P2 component of Chinese subjects for the vowel /mu/

	left P2 [nAm · s]				right P2 [nAm · s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	7	11	-8	28	9	22	6	11
VPN 2	-8	-7	-15	-8	6	0	4	5
VPN 3	13	8	3	6	7	-4	-6	-2
VPN 4	2	7	-2	4	-6	0	-12	-3
VPN 5	13	13	2	20	6	7	4	10
VPN 6	5	11	3	20	10	5	3	9
VPN 7	5	3	5	-5	4	1	-4	0
VPN 8	10	16	11	26	23	20	7	24
VPN 9	16	17	13	15	15	10	1	-6
VPN 10	19	20	3	1	8	20	-5	13
VPN 11	56	24	15	54	46	8	37	15
VPN 12	2	-1	-5	-1	15	-7	-7	-5
VPN 13	8	9	9	20	14	9	10	18
VPN 14	-3	2	-2	1	15	4	6	6
VPN 15	17	18	6	4	10	6	13	-7
VPN 16	18	12	4	10	24	15	9	22
VPN 17	41	11	15	14	34	10	11	18
VPN 18	27	8	17	2	23	12	11	16
VPN 19	9	4	4	-1	-1	10	-10	0
VPN 20	13	16	3	13	39	44	58	45
Mean	13.5	10.1	4.1	11.2	15.1	9.6	6.8	9.5
Std Dev	14.6	7.5	8.1	14.4	13.2	11.2	16.1	12.7
Std Err	3.3	1.7	1.8	3.2	2.9	2.5	3.6	2.8

Table B.27: P2 component of Chinese subjects for the vowel /o/

	left P2 [nAm · s]				right P2 [nAm · s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	8	4	-5	4	1	9	-2	8
VPN 2	-3	-5	-20	-3	1	-14	-31	6
VPN 3	3	6	1	12	-13	-4	-3	11
VPN 4	-2	-7	-11	-4	-4	-19	-17	-5
VPN 5	20	21	11	12	25	18	3	11
VPN 6	10	10	10	5	4	11	-2	-2
VPN 7	-3	0	-11	-3	2	-2	-6	-1
VPN 8	38	10	19	13	30	16	9	30
VPN 9	0	-4	6	7	-8	-7	1	-5
VPN 10	13	12	-3	2	16	-2	-5	-4
VPN 11	63	56	35	50	44	20	7	51
VPN 12	-6	5	-14	1	1	4	4	7
VPN 13	15	12	3	16	28	12	11	19
VPN 14	-2	-1	1	1	5	6	0	6
VPN 15	37	5	0	9	12	9	-12	-16
VPN 16	2	-1	7	11	9	16	11	14
VPN 17	29	11	6	27	30	18	13	23
VPN 18	7	11	-6	8	5	8	-10	17
VPN 19	11	11	-2	0	6	8	-4	1
VPN 20	14	10	15	23	46	42	41	40
Mean	12.7	8.3	2.1	9.6	12.0	7.5	0.4	10.6
Std Dev	17.5	13.3	12.5	12.7	16.6	13.5	14.2	16.2
Std Err	3.9	3.0	2.8	2.8	3.7	3.0	3.2	3.6

Table B.28: P2 component of Chinese subjects for the vowel /ö/

	left P2 [nAm·s]				right P2 [nAm·s]			
subject	**/ö1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	26	35	44	42	72	77	98	49
VPN 2	12	15	10	20	8	6	-6	-3
VPN 3	9	9	-1	10	4	16	8	35
VPN 4	2	3	-12	-1	8	15	-9	12
VPN 5	38	52	5	48	25	38	0	35
VPN 6	39	25	36	63	32	14	34	54
VPN 7	8	20	35	33	39	15	17	57
VPN 8	19	54	8	38	24	44	30	26
VPN 9	12	9	8	19	5	6	3	10
VPN 10	21	18	10	36	22	16	19	23
VPN 11	9	14	3	-2	24	-2	-4	-7
VPN 12	22	4	8	17	17	22	9	17
VPN 13	32	31	50	37	20	11	42	29
VPN 14	16	14	15	6	5	11	18	13
VPN 15	-3	2	-9	-3	4	16	3	9
VPN 16	11	33	11	54	31	47	40	62
VPN 17	28	43	36	54	-7	23	28	23
VPN 18	34	41	29	32	21	11	6	15
VPN 19	95	19	24	44	80	27	42	51
VPN 20	42	34	26	23	32	9	15	26
Mean	23.6	23.8	16.8	28.5	23.3	21.1	19.7	26.8
Std Dev	21.1	15.9	17.3	19.9	21.7	18.2	24.5	19.8
Std Err	4.7	3.6	3.9	4.4	4.8	4.1	5.5	4.4

Table B.29: P2 component of German subjects for the vowel /ma/

	left P2 [nAm · s]				right P2 [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	19	16	14	19	21	45	22	46
VPN 2	39	20	-6	9	24	5	-9	-3
VPN 3	29	19	12	41	28	13	13	15
VPN 4	1	-2	6	6	9	1	7	6
VPN 5	33	28	-3	18	18	25	-2	22
VPN 6	18	22	11	25	29	17	4	25
VPN 7	37	75	15	60	12	44	11	98
VPN 8	16	7	12	26	27	19	26	30
VPN 9	6	13	3	2	6	12	4	6
VPN 10	13	9	29	39	9	21	8	10
VPN 11	6	5	9	-4	9	10	4	5
VPN 12	2	22	-1	6	5	12	-1	14
VPN 13	35	16	23	25	33	4	16	17
VPN 14	22	0	8	18	11	12	9	12
VPN 15	19	2	-32	-8	5	0	-4	3
VPN 16	4	18	32	16	28	39	37	35
VPN 17	36	23	5	16	30	10	-6	-1
VPN 18	20	22	4	27	7	16	11	9
VPN 19	28	43	-2	16	30	50	2	9
VPN 20	27	36	19	32	8	51	12	28
Mean	20.5	19.7	7.9	19.5	17.5	20.3	8.2	19.3
Std Dev	12.3	17.3	13.8	16.1	10.2	16.5	11.2	22.4
Std Err	2.8	3.9	3.1	3.6	2.3	3.7	2.5	5.0

Table B.30: P2 component of German subjects for the vowel /mu/

	left P2 [nAm·s]				right P2 [nAm·s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	21	52	27	40	64	49	87	55
VPN 2	23	20	19	19	-7	0	-1	-3
VPN 3	42	41	35	35	48	32	29	32
VPN 4	0	2	-9	6	4	-8	-11	11
VPN 5	67	24	54	37	18	42	27	38
VPN 6	42	21	18	59	26	40	17	40
VPN 7	25	30	55	68	10	40	67	32
VPN 8	21	35	16	29	28	29	21	17
VPN 9	2	7	1	7	-3	1	-5	2
VPN 10	26	39	21	33	24	37	23	30
VPN 11	30	3	10	5	3	17	1	21
VPN 12	5	41	41	8	14	17	15	7
VPN 13	51	42	21	40	31	28	18	24
VPN 14	15	25	5	9	20	12	7	14
VPN 15	11	4	-4	-9	-1	-3	7	-2
VPN 16	16	5	19	5	19	1	24	20
VPN 17	14	14	15	11	-3	-3	-5	-3
VPN 18	13	25	20	46	9	15	4	6
VPN 19	30	42	5	23	17	32	21	29
VPN 20	30	28	28	20	3	26	10	7
Mean	24.2	25.0	19.9	24.6	16.2	20.2	17.8	18.9
Std Dev	16.7	15.4	17.1	20.1	17.8	17.7	23.5	16.1
Std Err	3.7	3.4	3.8	4.5	4.0	4.0	5.3	3.6

Table B.31: P2 component of German subjects for the vowel /o/

	left P2 [nAm·s]				right P2 [nAm·s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	58	25	57	28	160	75	66	69
VPN 2	30	6	10	13	2	-17	-7	-6
VPN 3	45	54	55	35	30	35	22	41
VPN 4	3	9	1	17	-2	10	14	14
VPN 5	86	33	-3	45	88	33	6	66
VPN 6	39	34	30	22	24	25	22	35
VPN 7	30	53	28	66	19	77	33	109
VPN 8	24	29	25	12	27	22	30	21
VPN 9	18	9	2	11	8	6	0	8
VPN 10	23	35	20	19	25	21	19	12
VPN 11	14	17	5	-6	29	-3	6	-4
VPN 12	9	20	16	15	17	36	10	45
VPN 13	43	26	29	45	38	19	17	33
VPN 14	26	16	5	19	25	16	9	17
VPN 15	-3	-6	-6	-3	3	0	-4	12
VPN 16	8	33	16	20	29	42	27	43
VPN 17	39	20	11	9	28	-4	-4	-2
VPN 18	35	38	21	65	13	51	4	11
VPN 19	17	62	18	26	31	44	40	13
VPN 20	39	35	11	35	29	18	-5	8
Mean	29.2	27.4	17.6	24.7	31.2	25.3	15.3	27.3
Std Dev	20.5	17.0	16.8	19.3	35.5	24.7	18.1	28.7
Std Err	4.6	3.8	3.8	4.3	7.9	5.5	4.0	6.4

Table B.32: P2 component of German subjects for the vowel /ö/

SF The sustained field starts at around 300 ms after tone onset with its peak at the end of the stimulus' length, leading to a fitting interval of $sim450 \pm 150$ ms.

	left SF [nAm·s]				right SF [nAm·s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	-9	-39	-51	-6	-35	-9	-13	-3
VPN 2	-101	-31	-73	-54	-52	-61	-93	-78
VPN 3	-66	-56	-60	-22	-44	-33	-46	-24
VPN 4	-27	-49	-41	-24	-41	-50	-30	-18
VPN 5	-15	-10	-4	-12	-43	-14	-10	-10
VPN 6	-52	-37	-36	-37	-60	-26	-54	-9
VPN 7	-80	-72	-75	-89	-81	-43	-85	-48
VPN 8	-40	-10	-47	-48	-69	-20	-18	-24
VPN 9	-48	-62	-44	-33	-38	-65	-55	-28
VPN 10	-109	-34	-57	-29	-78	-57	-54	-37
VPN 11	-54	-32	-52	-30	-69	-38	-77	-38
VPN 12	-40	-32	-45	-59	-55	-25	-63	-64
VPN 13	-66	-37	-66	-23	-21	-20	-23	-9
VPN 14	-40	-17	-33	-36	-53	-30	-43	-25
VPN 15	-41	-79	-63	-30	-38	-83	-55	-44
VPN 16	-21	-23	-15	-18	-29	-17	-80	-27
VPN 17	-41	-18	-26	-11	-46	-39	-50	-21
VPN 18	-109	-65	-55	-68	-51	-59	-58	-77
VPN 19	-43	-46	-33	-32	-30	-34	-43	-35
VPN 20	-91	-77	-48	-5	-46	-27	-39	-43
Mean	-54.7	-41.3	-46.2	-33.3	-49.0	-37.5	-49.5	-33.1
Std Dev	29.9	21.4	18.2	21.4	16.2	19.6	23.4	21.3
Std Err	6.7	4.8	4.1	4.8	3.6	4.4	5.2	4.8

Table B.33: SF component of Chinese subjects for the vowel /ma/

	left SF [nAm · s]				right SF [nAm · s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	-27	-30	-45	-8	-21	-9	-28	-2
VPN 2	-47	-65	-59	-39	-57	-70	-73	-29
VPN 3	-47	-30	-46	-35	-21	-20	-35	-20
VPN 4	-62	-35	-36	-12	-48	-35	-36	-11
VPN 5	-28	-19	-21	-7	-30	-25	-27	-15
VPN 6	-35	-44	-40	-26	-30	-31	-55	-40
VPN 7	-48	-80	-137	-63	-59	-62	-97	-52
VPN 8	-69	-29	-55	-42	-49	-71	-65	-57
VPN 9	-44	-64	-61	-39	-47	-30	-45	-44
VPN 10	-53	-26	-36	-39	-56	-44	-42	-39
VPN 11	-46	-34	-49	-11	-43	-46	-40	-51
VPN 12	-28	-26	-28	-24	-32	-31	-67	-78
VPN 13	-40	-44	-63	-40	-12	-11	-20	-27
VPN 14	-59	-35	-27	-37	-35	-24	-28	-32
VPN 15	-20	-49	-32	-31	-38	-37	-59	-16
VPN 16	-27	-22	-21	-11	-18	-71	-21	-23
VPN 17	-27	-56	-48	-13	-53	-57	-59	-31
VPN 18	-66	-66	-47	-46	-38	-61	-52	-73
VPN 19	-31	-34	-55	-22	-40	-47	-38	-42
VPN 20	-37	-19	-45	-6	-27	-30	-22	-18
Mean	-42.1	-40.4	-47.6	-27.6	-37.7	-40.6	-45.5	-35.0
Std Dev	14.5	17.6	24.6	15.9	13.8	19.5	20.3	20.1
Std Err	3.2	3.9	5.5	3.6	3.1	4.4	4.5	4.5

Table B.34: SF component of Chinese subjects for the vowel /mu/

	left SF [nAm·s]				right SF [nAm·s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-41	-52	-58	-29	-24	-12	-13	-23
VPN 2	-50	-23	-27	-59	-44	-26	-52	-24
VPN 3	-39	-31	-84	-10	-31	-45	-48	-13
VPN 4	-30	-23	-21	-24	-20	-10	-16	-16
VPN 5	-20	-26	-19	-6	-16	-25	-34	-13
VPN 6	-21	-27	-38	-41	-27	-16	-22	-34
VPN 7	-66	-76	-70	-61	-67	-78	-73	-57
VPN 8	-25	-33	-15	-11	-29	-42	-33	-31
VPN 9	-22	-42	-53	-27	-35	-48	-40	-40
VPN 10	-37	-19	-35	-37	-34	-22	-23	-43
VPN 11	-32	-15	-54	-30	-28	-35	-42	-22
VPN 12	-24	-22	-39	-14	-24	-39	-53	-48
VPN 13	-18	-30	-23	-55	-1	-4	-4	-10
VPN 14	-18	-15	-27	-20	-18	-28	-22	-24
VPN 15	-4	-19	-7	-11	-6	-16	-14	-9
VPN 16	-31	-11	-13	-57	-28	-32	-21	-17
VPN 17	-31	-20	-39	-17	-34	-34	-44	-48
VPN 18	-46	-87	-39	-52	-49	-40	-20	-29
VPN 19	-28	-65	-36	-31	-36	-38	-56	-34
VPN 20	-17	-9	-26	-3	-45	-8	-43	-5
Mean	-30.0	-32.3	-36.2	-29.8	-29.8	-29.9	-33.7	-27.0
Std Dev	13.9	21.7	19.7	18.9	14.9	17.3	17.8	14.7
Std Err	3.1	4.8	4.4	4.2	3.3	3.9	4.0	3.3

Table B.35: SF component of Chinese subjects for the vowel /o/

	left SF [nAm·s]				right SF [nAm·s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	-29	-42	-13	-27	-5	-18	-7	-13
VPN 2	-37	-17	-37	-26	-36	-30	-48	-30
VPN 3	-39	-22	-30	-37	-41	-25	-37	-19
VPN 4	-36	-25	-56	-35	-21	-21	-52	-31
VPN 5	-8	-11	-30	-6	-10	-11	-67	-7
VPN 6	-27	-22	-41	-26	-27	-21	-28	-13
VPN 7	-74	-76	-82	-57	-49	-66	-72	-65
VPN 8	-29	-39	-51	-15	-50	-36	-36	-8
VPN 9	-55	-44	-100	-36	-26	-31	-81	-16
VPN 10	-38	-9	-40	-14	-19	-14	-41	-5
VPN 11	-29	-12	-29	-16	-23	-22	-38	-29
VPN 12	-16	-14	-35	-22	-25	-29	-86	-47
VPN 13	-26	-48	-35	-22	-7	-1	-7	-13
VPN 14	-27	-11	-14	-13	-31	-27	-45	-14
VPN 15	-8	-19	-4	-5	-6	-24	-10	-21
VPN 16	-44	-14	-15	-14	-53	-41	-22	-29
VPN 17	-29	-21	-33	-40	-39	-60	-36	-39
VPN 18	-63	-42	-57	-34	-19	-79	-67	-22
VPN 19	-11	-21	-60	-40	-23	-62	-73	-33
VPN 20	-41	-15	-7	-21	-18	-2	-10	-14
Mean	-33.3	-26.2	-38.5	-25.3	-26.4	-31.0	-43.2	-23.4
Std Dev	17.1	17.1	24.3	13.2	14.5	21.1	25.0	14.9
Std Err	3.8	3.8	5.4	2.9	3.3	4.7	5.6	3.3

Table B.36: SF component of Chinese subjects for the vowel /ö/

	left SF [nAm · s]				right SF [nAm · s]			
subject	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**	**/ma1/**	**/ma2/**	**/ma3/**	**/ma4/**
VPN 1	-11	-4	-8	-6	-9	-23	-11	-5
VPN 2	-48	-48	-39	-48	-32	-28	-22	-47
VPN 3	-35	-36	-28	-22	-26	-11	-15	-12
VPN 4	-54	-65	-77	-96	-29	-54	-69	-48
VPN 5	-29	-7	-18	-30	-55	-20	-40	-24
VPN 6	-27	-7	-20	-8	-25	-9	-20	-5
VPN 7	-5	-25	-18	-20	-9	-6	-18	-10
VPN 8	-19	-16	-74	-18	-28	-5	-14	-5
VPN 9	-35	-27	-34	-34	-41	-43	-30	-31
VPN 10	-8	-8	-17	-6	-21	-6	-12	-8
VPN 11	-48	-28	-63	-37	-40	-31	-69	-50
VPN 12	-28	-7	-43	-22	-25	-11	-36	-23
VPN 13	-15	-21	-37	-15	-17	-23	-27	-4
VPN 14	-56	-7	-27	-14	-36	-5	-13	-28
VPN 15	-68	-42	-57	-19	-52	-32	-37	-64
VPN 16	-24	-25	-17	-21	-29	-18	-16	-14
VPN 17	-18	-11	-13	-13	-35	-13	-17	-11
VPN 18	-46	-10	-33	-41	-45	-11	-31	-14
VPN 19	-14	-48	-77	-21	-22	-8	-68	-16
VPN 20	-30	-21	-46	-28	-76	-2	-54	-57
Mean	-30.9	-23.2	-37.3	-26.0	-32.6	-18.0	-31.0	-23.8
Std Dev	17.6	17.1	22.0	20.0	16.0	13.9	19.7	19.3
Std Err	3.9	3.8	4.9	4.5	3.6	3.1	4.4	4.3

Table B.37: SF component of German subjects for the vowel /ma/

	left SF [nAm·s]				right SF [nAm·s]			
subject	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**	**/mu1/**	**/mu2/**	**/mu3/**	**/mu4/**
VPN 1	-18	-9	-6	-8	-39	-7	-25	-13
VPN 2	-17	-37	-66	-30	-19	-32	-35	-23
VPN 3	-21	-5	-42	-9	-29	-11	-32	-11
VPN 4	-88	-67	-75	-65	-34	-49	-49	-26
VPN 5	-27	-16	-32	-34	-39	-41	-30	-48
VPN 6	-22	-6	-22	-11	-24	-11	-11	-9
VPN 7	-7	-9	-15	-25	-7	-15	-11	-32
VPN 8	-11	-23	-37	-16	-26	-11	-53	-8
VPN 9	-42	-58	-41	-59	-42	-34	-29	-61
VPN 10	-13	-10	-14	-8	-6	-32	-21	-16
VPN 11	-46	-56	-40	-39	-51	-54	-37	-41
VPN 12	-22	-21	-31	-19	-24	-16	-27	-33
VPN 13	-28	-10	-26	-25	-13	-13	-8	-12
VPN 14	-83	-25	-53	-29	-40	-17	-43	-18
VPN 15	-61	-61	-83	-48	-58	-41	-66	-38
VPN 16	-66	-31	-38	-21	-82	-16	-34	-20
VPN 17	-16	-18	-16	-7	-27	-28	-19	-28
VPN 18	-44	-34	-36	-20	-15	-31	-36	-8
VPN 19	-30	-12	-20	-13	-27	-10	-32	-19
VPN 20	-21	-46	-74	-47	-54	-29	-36	-45
Mean	-34.2	-27.7	-38.4	-26.7	-32.8	-24.9	-31.7	-25.5
Std Dev	23.7	20.1	21.9	17.3	18.7	14.1	14.3	15.1
Std Err	5.3	4.5	4.9	3.9	4.2	3.2	3.2	3.4

Table B.38: SF component of German subjects for the vowel /mu/

	left SF [nAm·s]				right SF [nAm·s]			
subject	**/o1/**	**/o2/**	**/o3/**	**/o4/**	**/o1/**	**/o2/**	**/o3/**	**/o4/**
VPN 1	-78	-28	-39	-1	-16	-4	-7	-34
VPN 2	-39	-20	-25	-35	-36	-9	-28	-15
VPN 3	-15	-13	-5	-7	-20	-21	-11	-14
VPN 4	-47	-48	-66	-46	-25	-22	-49	-31
VPN 5	-10	-20	-19	-29	-13	-24	-29	-42
VPN 6	-18	-10	-3	-22	-9	-15	-15	-4
VPN 7	-26	-31	-14	-2	-15	-23	-15	-11
VPN 8	-28	-25	-21	-4	-2	-8	-16	-10
VPN 9	-40	-21	-39	-37	-43	-23	-41	-31
VPN 10	-5	-1	-12	-4	-9	-6	-5	-7
VPN 11	-65	-51	-58	-80	-48	-50	-46	-49
VPN 12	-22	-10	-30	-18	-18	-10	-35	-7
VPN 13	-5	-14	-28	-19	-3	-10	-21	-12
VPN 14	-70	-17	-75	-12	-34	-27	-36	-27
VPN 15	-31	-19	-49	-20	-52	-40	-43	-31
VPN 16	-21	-27	-47	-26	-45	-9	-40	-16
VPN 17	-21	-14	-35	-6	-39	-14	-37	-25
VPN 18	-13	-16	-32	-12	-16	-4	-13	-48
VPN 19	-18	-27	-28	-16	-14	-23	-39	-22
VPN 20	-47	-54	-35	-54	-40	-25	-40	-11
Mean	-31.0	-23.3	-33.0	-22.5	-24.9	-18.4	-28.3	-22.4
Std Dev	21.2	14.0	19.1	20.1	15.8	12.0	14.1	13.8
Std Err	4.7	3.1	4.3	4.5	3.5	2.7	3.2	3.1

Table B.39: SF component of German subjects for the vowel /o/

	left SF [nAm · s]				right SF [nAm · s]			
subject	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**	**/ö1/**	**/ö2/**	**/ö3/**	**/ö4/**
VPN 1	-21	-15	-8	-5	-22	-3	-6	-20
VPN 2	-25	-30	-47	-37	-18	-49	-31	-13
VPN 3	-14	-4	-6	-13	-13	-6	-9	-17
VPN 4	-46	-85	-50	-76	-27	-80	-37	-24
VPN 5	-30	-19	-16	-40	-42	-24	-13	-49
VPN 6	-8	-12	-12	-5	-6	-10	-25	-5
VPN 7	-32	-21	-15	-7	-13	-29	-27	-28
VPN 8	-5	-18	-15	-10	-5	-9	-2	-4
VPN 9	-63	-37	-41	-28	-42	-35	-32	-35
VPN 10	-8	-8	-4	-10	-9	-9	-9	-5
VPN 11	-84	-60	-57	-71	-45	-44	-60	-52
VPN 12	-41	-20	-42	-23	-25	-19	-78	-22
VPN 13	-10	-8	-20	-13	-10	-13	-9	-6
VPN 14	-27	-62	-59	-10	-28	-32	-35	-25
VPN 15	-26	-39	-46	-26	-39	-33	-56	-30
VPN 16	-22	-21	-26	-40	-23	-31	-32	-39
VPN 17	-12	-4	-15	-5	-22	-10	-24	-5
VPN 18	-29	-22	-30	-21	-18	-43	-34	-11
VPN 19	-5	-39	-19	-48	-7	-33	-26	-26
VPN 20	-17	-18	-40	-22	-14	-28	-49	-17
Mean	-26.3	-27.1	-28.4	-25.5	-21.4	-27.0	-29.7	-21.7
Std Dev	20.1	21.3	17.8	21.0	12.6	18.5	19.7	14.4
Std Err	4.5	4.8	4.0	4.7	2.8	4.1	4.4	3.2

Table B.40: SF component of German subjects for the vowel /ö/

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