

# **The effects of background noise on asymmetrical speech perception**

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*In memory of my beloved grandmother*

*“Wäre das menschliche Gehirn so simpel, dass wir es erfassen könnten,  
wären wir so simpel, dass wir es nicht könnten.“*

Immanuel Kant



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## ABSTRACT

The present thesis aimed at examining the effects of environmental background noise on asymmetrical speech perception. To assess asymmetrical speech perception, the Bergen Dichotic Listening (DL) task with consonant-vowel (CV) syllables was performed. In Report I, two background noises (traffic and ‘babble’) were presented while healthy subjects performed the DL task. In Report II, the intensity of the two background noises varied to additionally study the effects of intensity level on DL performance. In Report III, the neuronal mechanisms behind the effect of background noise on DL performance were studied by measuring hemodynamic brain responses using functional magnetic resonance imaging (fMRI). The behavioral data of the three Reports point in the same direction: They revealed a modulation of the typical right-ear advantage (REA) in DL to CV-syllables, especially in traffic background noise, which was due to a decrease in right ear correct reports while left ear correct reports increased. Intensity level was observed to play an additional modulating role that intensified the noise effect with increasing intensity level. The behavioral noise effect was even shown when fMRI was done simultaneously in Report III. The behavioral results are discussed in terms of alertness and attentional mechanisms. fMRI data did not reveal an one-to-one mapping of the behavioral data, however showed different activation patterns especially in the peri-Sylvian region, superior temporal gyrus (STG)/superior temporal sulcus (STS) and STG/supramarginal gyrus (SMG). Pre-activation mechanisms due to noise are proposed to influence subsequent processing of CV-syllables resulting in the observed modulation of behavioral REA. The thesis provides new knowledge to laterality research, especially research in DL. Furthermore, by using day-to-day noises, the thesis brings forward noise research, and stimulates future research in those areas.





## ABBREVIATIONS

<b>ANOVA</b>	Analysis Of Variance
<b>BNC</b>	Background Noise Conversation / Babble
<b>BNC_CV</b>	Consonant-Vowel Syllable Pairs With Babble Background Noise
<b>BNT</b>	Background Noise Traffic
<b>BNT_CV</b>	Consonant-Vowel Syllable Pairs With Traffic Background Noise
<b>BOLD</b>	Blood Oxygen Level Dependent
<b>CV</b>	Consonant-Vowel
<b>dB</b>	Decibel
<b>DL</b>	Dichotic Listening
<b>EEG</b>	Electroencephalography
<b>EPI</b>	Echo-Planar Imaging
<b>ERPs</b>	Event-Related Potentials
<b>FDR</b>	False Discovery Rate
<b>fMRI</b>	Functional Magnetic Resonance Imaging
<b>FOV</b>	Field Of View
<b>FWE</b>	Family-Wise Error
<b>FWHM</b>	Full Width at Half Maximum
<b>GLM</b>	General linear model
<b>HG</b>	Heschl's Gyrus
<b>hrf</b>	Hemodynamic Response Function
<b>Hz</b>	Hertz
<b>LEA</b>	Left-Ear Advantage
<b>LI</b>	Laterality Index
<b>MEG</b>	Magnetoencephalography
<b>MNI</b>	Montreal Neurological Institute
<b>MMN</b>	Mismatch Negativity
<b>MMNm</b>	Magnetic Mismatch Negativity
<b>MRI</b>	Magnetic Resonance Imaging
<b>MTG</b>	Middle Temporal Gyrus
<b>PET</b>	Positron Emission Tomography
<b>PP</b>	Planum Polare
<b>PT</b>	Planum Temporale
<b>REA</b>	Right-Ear Advantage
<b>ROI</b>	Region Of Interest
<b>SMG</b>	Supramarginal Gyrus
<b>SPM</b>	Statistical Parametric Mapping
<b>STG</b>	Superior Temporal Gyrus
<b>STS</b>	Superior Temporal Sulcus
<b>TE</b>	Echo Time
<b>TMS</b>	Transcranial Magnetic Stimulation
<b>TR</b>	Repetition Time



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## LIST OF PAPERS

- I. Dos Santos Sequeira, S., Specht, K., Hämäläinen, H., & Hugdahl, K. (2008). The effects of background noise on dichotic listening to consonant-vowel syllables. *Brain and Language*, *107*, 11-15.
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## 1. Hemispheric asymmetry of speech perception

### 1.1. Hemispheric asymmetry

Hemispheric asymmetry denotes structural or morphological differences between the left and the right hemisphere (Hellige, 1993; Jäncke & Steinmetz, 2003). Asymmetry (or laterality) also denotes differences in the capacity for information processing between the right and left cerebral hemispheres (Hugdahl, 2003).

At first glance, the gross anatomy of the human body along the vertical axis gives the impression of an almost anatomically perfect mirror symmetrical organization of the body. Additionally, the almost symmetrical mirror image of the surfaces of the two cerebral hemispheres may suggest that also the left and the right halves of the brain have a certain symmetrical organization, not only anatomically but also functionally (see Hugdahl, 2005). However, from humans to animals, normal variation and specialization of the brain for example due to evolutionary or pathological factors have produced asymmetry of structure and function (Toga & Thompson, 2003). Thus, the first impressions when looking at the brain is misleading and research has shown that the two halves of the brain are not symmetrical (e.g. Kimura, 1973; Zaidel, Chen, & German, 1995). The left and the right hemispheres are not only structurally different, but also asymmetrically organized regarding different functions.

The concept of asymmetry regarding various structures and functions in the two hemispheres of the human brain will be outlined in more detail in the following with emphasis on speech perception.

### 1.2. Anatomical asymmetry

Right-left macroscopic anatomical differences in the brain have been observed for over a century (Eberstaller, 1884) and can be found for gross features of both hemispheres as well as for specific brain areas within a hemisphere. This involves gyrfication patterns, and the form and length of certain sulci, as well as the overall shape of the two hemispheres. Structural brain asymmetries exhibit a great deal of individual variation, modulated by factors such as handedness (e.g. Steinmetz, Volkman, Jäncke, & Freund, 1991), sex (e.g. Beaton, 1997), and

pathophysiology (e.g. Gur & Chin, 1999). In schizophrenia for example, reduction of grey matter volume in the left hemisphere was observed (Neckelmann et al., 2006).

A marked anatomical asymmetry is the protrusion of the right frontal pole and the protrusion of the left occipital pole, that produce imprints on the inner surface of the skull, known as petalia (e.g. Cunningham, 1892; Zilles et al., 1996). Another well-documented brain asymmetry is in Broca's area, an area covering the triangular and opercular part of the left inferior frontal gyrus, which is found to have a larger volume than its homologue in the right hemisphere (e.g. Amunts et al., 1999). Furthermore, the central sulcus, that separates the frontal and parietal lobes, is reported to be deeper on the left than on the right side (Amunts et al., 1996). Anatomical asymmetries can also be found in the arcuate fasciculus bundle that connects the anterior temporal and inferior frontal lobes, with the left bundle being thicker than the right, which probably reflects the functional asymmetry of language processing (Glasser & Rilling, 2008; Vernooij et al., 2007). The thalamus, which plays a significant role in filtering, gating, processing, and relying information, has also been found to exhibit side differences, with the lateral nuclei having a left-, and the dorsal nuclei having a right-sided asymmetry (Watkins et al., 2001, see also Deicken, Eliaz, Chosiad, Feiwell, & Rogers, 2002). Asymmetries concerning the lateral surface of the brain in the peri-Sylvian region have received by far the most attention in the literature. It was the asymmetrical trajectory of the Sylvian fissure that was one of the first anatomical interhemispheric differences to be described. The left Sylvian fissure was observed to be longer and running less steep than the right (e.g. Eberstaller, 1884; Narr et al., 2001). Moreover, the posterior tip of the Sylvian fissure was found to be higher on the right side (Hochberg & LeMay, 1975). Within the Sylvian fissure, the transverse temporal gyrus (Heschl's gyrus, HG), which corresponds to the primary auditory cortex, shows marked right-left variation, with the left being larger (e.g. Pfeifer, 1920, 1936; Rademacher, Caviness, Steinmetz, & Galaburda, 1993). It has also been found that there are mostly two HG on the left, but only one on the right hemisphere (Chi, Dooling, & Gilles, 1977). Another anatomical region that is found to exhibit side differences is the planum temporale (PT). The PT is a roughly triangular region, which is located in the superior temporal gyrus (STG), in the depth in the Sylvian fissure, posterior to the first (anterior) HG. The presence of a larger PT in the left hemisphere was first observed at autopsy (Pfeifer, 1920; von Economo & Horn, 1930), but not confirmed and quantified until 1968 by Geschwind and Levitsky (Geschwind & Levitsky, 1968). Ever since, a large and diverse literature has emerged concerning the anatomical asymmetry of this region (e.g. Dos Santos Sequeira et al., 2006; see Shapleske, Rossell, Woodruff, & David, 1999 for a review).



A neighboring region to the PT is the planum parietale (PP). It is defined as the cortex covering the posterior wall of the posterior ascending Sylvian ramus. It has been shown that the direction of the PP asymmetry is opposite to that of the PT asymmetry (Binder, Frost, Hammeke, Rao, & Cox, 1996), however weakly correlated (Jäncke, Schlaug, Huang, & Steinmetz, 1994). In front of the PT, on the opposite bank of the Sylvian fissure, lies the parietal operculum that also displays structural right-left variation (e.g. LeMay & Culebras, 1972), with the left being larger than the right in most right-handers (Habib, Robichon, Levrier, Khalil, & Salamon, 1995).

### 1.3. Functional asymmetry of speech perception

Functional asymmetry has been demonstrated for a variety of sensory, motor and cognitive functions, such as mental rotation (Johnson, McKenzie, & Hamm, 2002), spatial processing (Kosslyn, 1987), and face recognition (Kelley et al., 1998), although the most well-known example of asymmetry of brain function is speech dominance, or speech specialization. The specialization of the left hemisphere for speech was one of the earliest observations of functional brain asymmetry (Springer & Deutsch, 1998).

The oldest, but still important, approach for the study of functional brain asymmetry is the observation of patients with brain injury restricted to one hemisphere or the other. Reported in the second half of the 19<sup>th</sup> century by Paul Broca (1861) and Carl Wernicke (1874), speech was found to be more severely impaired in response to lesions in the left hemisphere. Whereas speech production has subsequently been confined primarily to areas in the inferior frontal gyrus (Broca's area), speech perception has been localized primarily to the upper posterior part of the temporal lobe (Wernicke's area). It was Wernicke who advanced the first theory of brain organization of speech. He postulated a reflex arc in which the left superior temporal gyrus, which contained the auditory images of words, acted on the third frontal convolution, which supported their articulation, suggesting that higher functions are anatomically segregated (see also Grabowski & Damasio, 2000).

Since these early reports, the relationship between functional asymmetry for speech, especially speech perception, and asymmetries observed in anatomy or structural brain organization, has been extensively reported in the literature. In the early 1930s, Wilder Penfield and colleagues pioneered the use of surgery as treatment for epilepsy patients (Penfield, 1932; Penfield & Erickson, 1941). To determine with precision the location of the

regions controlling speech in a given patient in order to avoid of harming these areas during surgery, Penfield and his associates developed a procedure that involved mapping these cortical regions by using direct electrical stimulation of the brain at the time of surgery. They revealed that speech was blocked by electrical stimulation of the left hemisphere, but rarely by that of the right (Penfield, 1972; Penfield & Jasper, 1954). Work by neurologist George Ojemann has confirmed and extended the earlier findings (see Ojemann, 2003 for a review). However, despite their long clinical history, functional lesion methods, with cortical stimulation being only an example of several other methods, have been implemented only recently in speech perception research (see Boatman, 2004 for a review). While direct cortical stimulation is an invasive, intra-operative approach, prior to (epilepsy-)surgery, transcranial magnetic stimulation (TMS) is a recently established, non-invasive method, where functional lesions can be generated and studied also in healthy subjects.

In the 1940s and 1950s, a new surgical procedure devised to reduce or alleviate symptoms of seizure activity in patients with epilepsy was introduced (Bogen & Vogel, 1963). The procedure is known as 'commissurotomy', and involved the surgical sectioning of the fibres through the corpus callosum to control spreading of seizure activity from one hemisphere to the other. To the surprise of the involved clinicians and researchers the operation resulted in no obvious behavioral or personality changes, only in subtle changes of behavior under specific experimental conditions. It was Roger Sperry who in the 1960s and 1970s used the commissurotomy procedure, also known as the "split-brain" procedure, to further investigate the functioning of the cerebral hemispheres (see Sperry, 1961; 1974). Sperry showed that each of the two hemispheres is specialized for unique motor, sensory, and cognitive functions. His experimental studies also yielded important information of the different functional organization in the left and the right hemispheres in relation to speech perception (Levy, Nebes, & Sperry, 1971; Sperry, 1974). Roger Sperry was awarded the Nobel Prize in 1981 for his discoveries of the functional specialization of the two hemispheres of the brain.

Besides electrocortical stimulation and the study of split-brain patients, the intracarotid amobarbital procedure, also known as the Wada-test, is another neuroscientific method which allows researchers to assess functional organization within a cerebral hemisphere and to investigate functional lateralization between the two hemispheres (Wada & Rasmussen, 1960). The Wada test is a clinical method performed with patients before surgical treatment of seizure disorders or tumors. During the Wada test, one hemisphere is anesthetized at a time (due to injection of the barbiturate sodium amobarbital into either the left or right femoral

artery) to determine the speech capabilities (as well as other cognitive and motor functions) of the contralateral “awake” hemisphere. Thus, the Wada test also represents an important tool for the study of each hemisphere’s function, especially speech functions. A study by Rasmussen and Milner (1977) revealed that in 96% of the 140 examined right-handers speech was located in the left hemisphere, while in the remaining 4% speech was located in the right hemisphere. In contrast, speech was left-lateralized in only 70% of the 122 examined left-handers, while 15% showed speech lateralized to the right and bilateral speech representation was observed in the remaining 15% (Rasmussen & Milner, 1977).

Since the Wada-test as well as the other mentioned procedures like cortical stimulation and commissurotomy is an invasive procedure that can only be applied for clinical reasons, it was important that also other, non-invasive tests were developed for use on healthy volunteers and for research purposes. Functional differences between the two hemispheres with regard to speech perception can for example be assessed by using a dichotic listening technique which uses different speech sounds that are simultaneously presented to the subject. The dichotic listening (DL) technique is described in more detail in Chapter 2. The advent of new brain imaging methods like positron emission tomography (PET) in the early 80s, and later of functional magnetic resonance imaging (fMRI) in the early 90s has also contributed to enlighten functional right-left differences. These imaging methods have allowed the researcher and clinician to reveal the underlying neuronal asymmetries, adding new evidence to the findings from experimental procedures like the DL technique. Since fMRI was used in one of the presented studies here, the key concepts of fMRI, pre-processing steps and the analysis of fMRI data will be introduced in Chapter 3.

Functional differences between the two hemispheres with regard to speech perception have also been explored by linking them to anatomical brain asymmetries. As already specified in Section 1.2. a larger left than right PT has been revealed in the majority of anatomical studies (Jäncke & Steinmetz, 2003). Since the PT overlaps with Wernicke’s area, and since it is also located posterior to HG, which makes up the primary auditory cortex, it is assumed that the PT region represents the anatomical substrate of left-hemispheric speech perception (see Foundas, Leonard, Gilmore, Fennell, & Heilman, 1994, but see also Moffat, Hampson, & Lee, 1998). However, the traditional view that the PT exhibits a significant difference in size favoring the left over the right largely depends on several factors, not only on the methodological approach (e.g. Barta et al., 1995) and the definitional criteria for the structure (Zetzsche et al., 2001), but also on interindividual variability (e.g. Dos Santos

Sequeira et al., 2006). The role of the PT in speech perception will be further discussed in Section 1.4.

#### 1.4. Models of speech perception

Speech perception corresponds to a hierarchical organization of successive processing stages, i.e. a process encompassing various stages of analysis, with auditory and acoustic-phonetic analysis as the earliest stages (Pisoni & Luce, 1987; Studdert-Kennedy, 1974, 1976). These stages are obligatory, pre-lexical processing stages in most models of speech perception (Boatman, 2004). Higher-level stages of speech perception include phonological, lexical, syntactic, and semantic processing (Boatman, 2004). Various (psycho-) linguistic models of speech perception are discussed in the literature such as the motor theory (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967), Stevens' analysis-by-synthesis model (Stevens & Halle, 1967; Stevens, 2002), or the featurally underspecified lexicon (FUL) model (Lahiri & Reetz, 2002). However, since these models are theoretical, linguistic models, which are not grounded on neurological and neuro-imaging observations, the focus in the present Section will be on models of speech perception that are basically raised from neurobiological findings.

##### *1.4.1 Classical model*

The classical view, based on data from aphasic patients with brain lesions, emphasized the importance of 'speech-specific' areas in the left cerebral hemisphere. According to the Wernicke-Broca-Lichtheim-Geschwind model (Broca, 1961; Geschwind, 1965; Lichtheim, 1885; Wernicke, 1874), speech perception is linked to a region in the posterior left superior temporal lobe (Wernicke's area). A cortical pathway (the arcuate fasciculus) then connects to Broca's area. Although this model has the virtue of simplicity, it is at best incomplete and falls short of explaining the complexities of speech processing. The model not only fails to account for the range of aphasic syndromes, but it is also oversimplified regarding the sub-processes of speech comprehension and production. Furthermore, the model is anatomically underspecified, since it has been shown that other cortical areas outside of the classical 'centers' also contribute to speech function (see Poeppel & Hickok, 2004 for a profound discussion of these criticisms).

#### *1.4.2. Neuroanatomical organization of speech perception*

Cytoarchitectonical studies have identified and classified architectonic distinct areas within the auditory cortex, contributing to the understanding that different speech functions may underlie different cortical areas. Such studies have revealed that the primary auditory cortex overlaps with the location of the most anterior part of the HG (e.g. Brodmann, 1909; von Economo & Horn, 1930), while non-primary auditory cortex extends across the surface of the supratemporal plane into the insula (Rivier & Clarke, 1997) and the frontal and parietal operculum (Galaburda & Sanides, 1980), segregated into planum polare and PT. Thus, the posterior third of the STG (Wernicke's area) is covered by an association cortex, which is clearly different from the primary auditory cortex located on HG (Galaburda, Sanides, & Geschwind, 1978; Galaburda & Sanides, 1980).

Further methodologies providing important data on the morphology of the auditory cortex and other speech relevant areas have been structural brain imaging methods, like voxel based morphometry (Ashburner & Friston, 2000) or measures of cortical thickness (Fischl & Dale, 2000), or irregularities of the cortical folding (Sandu, Specht, Beneventi, Lundervold, & Hugdahl, 2008). Studying brain structures in vivo has improved the understanding of the neuronal basis of speech perception and advanced the view of speech organization in the brain prevailing at that time. The advent of structural brain imaging also offered a new possibility to study the PT in vivo and to further explore the initial hypothesis of the PT as being an anatomical substrate of speech perception (e.g. Hugdahl et al., 1999; Jäncke, Schlaug, Huang, & Steinmetz, 1994; Steinmetz et al., 1989, 1990, 1991; Zatorre, Perry, Beckett, Westbury, & Evans, 1998).

With the advent of functional imaging studies it became possible to reveal more differentiated and complex models of cortical organization of the different linguistic and cognitive processes contributing to speech perception.

#### *1.4.3. Functional neuroimaging of speech perception*

Non-invasive functional imaging studies have challenged the traditional view of speech perception being merely processed in the left hemisphere, and of the PT being involved in speech-specific or speech-selective processes (e.g. Binder et al., 1996). Speech perception was indicated to undergo discrete processing stages in the human brain with areas outside of the classical regions also contributing to those different processes (see Boatman, 2004 and

Poeppel & Hickok, 2004 for reviews). Although much neuroimaging research has been devoted to these issues over the last years, many aspects are still unsettled.

At a low level, speech perception includes the analysis of different basic acoustic cues such as temporal and spectral information, frequency, pitch, sound level, with the left and the right posterior STG being capable to extract and analyze the acoustic features of sound (Hall, Hart, & Johnsrude, 2003). These spectro-temporal computations executed in left and right auditory areas are however not identical (Hickok & Poeppel, 2000, 2007). Zatorre and colleagues have argued that the left hemisphere superior temporal areas are selectively involved in temporal analysis and that in contrast the right hemisphere areas are better suited to the processing of spectral properties of signals (Zatorre, 1997; Zatorre, Belin, & Penhune, 2002). Their view converges with that of Poeppel and colleagues (Poeppel, 2001; Poeppel, 2003; Poeppel, Idsardi, & van Wassenhove, 2008), who suggested that the functional asymmetry is a consequence of the size of the temporal integration windows of the neuronal ensembles in these areas. Griffiths and Warren (2002) ascribe these processes of segregating complex spectro-temporal patterns of the acoustic stimulus and matching these components with learned representations especially to the PT (Griffiths & Warren, 2002). Thus, asymmetries in speech perception may be related to low-level acoustic processing differences in the auditory cortices (Belin et al., 1998). However, attempts to demonstrate a speech-specific or speech-selective neuronal response in the PT have generally failed (Binder et al., 1996). Furthermore, it was shown that the PT is as sensitive for tones as it is for speech (Binder et al., 2000), thus it has no intrinsic specialization for speech per se. Rather it is involved in various types of early acoustic analysis, which are not speech-specific (e.g. Binder et al., 1997; Obleser, Zimmermann, Van Meter, & Rauschecker, 2007; Scott, Blank, Rosen, & Wise, 2000; Uppenkamp, Johnsrude, Norris, Marslen-Wilson, & Patterson, 2006; see Cabeza & Nyberg, 2000 for an overview).

Beyond a bilateral spectro-temporal analysis, there is accumulating evidence that speech perception is lateralized. Acoustic-to-phonetic mapping, including extraction of phonetic information, and phonological-level processing, where the phonetic segment is converted to systematic phoneme (Chomsky, 1966), have been suggested to involve middle to posterior portions of the superior temporal sulcus (STS) (Hickok & Poeppel, 2007). Several studies have found the STS region to be strongly left-dominant, while other studies suggest a bilateral organization with a weak left-hemisphere dominance bias (e.g. Binder et al., 2000; Démonet et al., 1992; Démonet, Price, Wise, & Frackowiak, 1994; Hickok & Poeppel, 2007; Jäncke, Wüstenberg, Scheich, & Heinze, 2002; Specht & Reul, 2003; Zatorre, Evans, Meyer,

& Gjedde, 1992). Posterior middle and inferior portions of the temporal lobes correspond to subsequent computations involving lexical access (lexical interface), which links phonological and semantic information (Indefrey & Levelt, 2004), more anterior portions of the temporal lobes may correspond to syntactic or combinatorial processes (Hickok & Poeppel, 2007, but see also Scott, Blank, Rosen, & Wise, 2000; Scott & Wise, 2004).

These results support the view of a hierarchical organization of auditory information processing, that is for example described in a functional neuroanatomical model of speech perception proposed by Hickok & Poeppel (2000, 2004, 2007). Subsequent to basic acoustic and phonological level processing, the authors suggest two broad pathways: The so-called ‘ventral’ pathway, involving posterior middle and inferior portions of the temporal lobes and anterior locations of the left temporal lobe might be responsible for the above described ‘sound-to-meaning mapping’, closely related to the ‘what’ pathway in the vision system (Ungerleider & Mishkin, 1982). A second segregated and parallel stream extends from the middle-posterior region of the STG (including the Sylvian-parietal-temporal area) to inferior parietal and frontal structures, also demonstrated to support speech perception (Hickok & Poeppel, 2000; Scott & Johnsrude, 2003). This left-lateralized ‘dorsal’ stream, may be important in linking the perception and production of speech (Davis & Johnsrude, 2003), i.e. for auditory-motor integration (Hickok & Poeppel, 2007), and is closely related to the ‘where’/‘how’ pathway in vision (Ungerleider & Mishkin, 1982). There have been several other suggestions and further developments concerning the functional specialization of parallel, hierarchical processing streams in the human auditory system (e.g. Belin & Zatorre, 2000; Binder et al., 2000; Glasser & Rilling, 2008).

Progress in neuroscience and contiguous fields may lead to continuous changes and improvements in those models of speech perception, with the aim to optimally combine (or unify, see Chomsky, 2000) the different perspectives of the brain and the language, approaching real understanding and explanation.

## 2. Dichotic listening

### 2.1. Definition and historical background

Dichotic listening (DL) literally means that two different auditory sounds are presented simultaneously, one to each ear. The DL procedure was originally invented by Donald Broadbent in 1954 to simulate the attentional problem faced by radar operators in the Second World War when receiving flight positions from more than one airplane at a time (Broadbent, 1954; see also Bryden, 1988). Broadbent presented strings of different digits simultaneously via earphones, one to the left ear and one to the right ear. When the presentation rate of the digits was fast, listeners tended to report the items first from one and then from the other ear. These findings have been explained by an early information-processing model (filter theory; Broadbent, 1958). In these early days, DL researchers merely focussed on the attentional and short-term memory parts of the phenomenon (Bryden, 1988). It was Doreen Kimura, who was the first researcher applying the DL technique in the field of neuropsychology, and thus advancing it into a tool for the study of hemispheric function, hemisphere asymmetry and brain laterality (Bryden, 1988; Hugdahl, 1995; Kimura, 1961, 1967).

### 2.2. Dichotic listening as a method to study the asymmetry of speech perception

In 1961, Kimura published two papers reporting results when she examined language lateralization functions in neurological patients and in healthy subjects by means of a DL technique with verbal material (digits), following Broadbent's general procedures (Kimura, 1961a, b). Many of the patients in Kimura's study (1961b) had also been tested with the Wada-test (Wada & Rasmussen, 1960), and it was shown that those patients with left-hemisphere language representation in the Wada-test recalled more accurate responses from the right ear in the DL procedure, while those with right-hemisphere language representation recalled more from the left ear. In a second study (1961a), Kimura reported, that the majority of healthy subjects showed more correct reports from the right ear, suggesting that the DL technique provides a non-invasive way assessing language lateralization in normal subjects (1961a)<sup>2</sup>. This so-called right-ear advantage (REA) for verbal material in most healthy

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<sup>2</sup> It may be of interest to note that Kimura used a recall paradigm in her first studies that involved requirements for working memory processing in addition to perceptual processing of the digits to be recalled.



subjects (including both right- and left-handers) has been taken as evidence for left-hemisphere lateralization for speech, while the left-ear advantage (LEA) occurring in only few subjects has been assumed to represent right-hemisphere speech processing. Since these first discoveries, there have been a vast amount of papers verifying Kimura's finding (e.g. Bryden, 1963; Satz, Achenbach, & Fennell, 1967), and meanwhile there have been developed several DL paradigms, which differ in type of stimulus material, number of items per trial, type of response, and instruction (see Hugdahl, 2008 for a description of different paradigms). Type of stimulus material that has been used may vary from verbal material, such as words, syllables, consonants, and digits to non-verbal material, such as tones, melodies, and environmental sounds. Responses may be freely reported (written or oral) or may be chosen from multiple possible answers (e.g. multiple choice). By instructing the subjects to attend to one ear for a block of trials and to report only the items presented to that ear, subject's attention can be explicitly directed to one or the other ear ('forced attention' or 'directed attention', Hugdahl & Andersson, 1986). In contrast, in the 'non-forced' or 'divided attention' instruction condition, the subjects are told to report the one stimulus they heard first or best or as many stimuli as they could remember in any order. The performances of both ears, indicated by the correct reproduced stimuli given to the particular ear, are then related to each other by calculating a laterality index (see Bruder, 1991 for a review of different laterality indices).

Across different paradigms, the REA has been proven to be a very robust finding for verbal material, no matter what variations were introduced (Bryden, 1988).

It was also Kimura who in 1964 provided the first evidence for a left-ear advantage (LEA) for musical stimuli, and other investigators have used musical chords (Gordon, 1980) to reveal a LEA, although test-retest reliability has been found to be only .46 (Blumstein, Goodglass, & Tartter, 1975; see however Hugdahl et al., 1999 who found a right hemisphere brain activation dominance to musical stimuli, see also Tervaniemi et al., 1999). Other non-verbal stimuli have involved tone contours (Colbourn & Lishman, 1979), complex tones (Sidtis, 1981), and common environmental sounds, such as a toilet flushing (Curry, 1967).

Compared to the Wada-test, the DL procedure represents a non-invasive, easy to use method to index language function (Studdert-Kennedy & Shankweiler, 1970; Tartter, 1988) that can also be used at the individual level. The DL test is in addition an important method to study attentional mechanisms and vigilance (Asbjørnsen & Hugdahl, 1995; Hugdahl, Thomsen, Ersland, Rimol, & Niemi, 2003; Løberg, Hugdahl, & Green, 1999), conditioning and learning (Dawson & Schell, 1982; Hugdahl & Brobeck, 1986), temporal lobe function

and memory (Hugdahl, Asbjørnsen, & Wester, 1993; Wester & Hugdahl, 1995; Wester, Lundervold, Taksdal, & Hugdahl, 1998), psycholinguistics (Repp, 1977; Lauter, 1982), and interhemispheric transfer and callosal function (Hugdahl, 1998; Hugdahl, Lundervold, von Plessen, Heiervang, & Rimol, 2003; Reinvang, Bakke, Hugdahl, Karlsen, & Sundet, 1994).

### 2.3. The Bergen DL test

Studdert-Kennedy and Shankweiler (1970) were the first to improve the early “crude” DL procedures by a better control over stimulus quality and timing. They used a DL paradigm with consonant-vowel-consonant (CVC) syllables with stop-consonants /b/, /d/, /g/, /p/, /t/, /k/, and obtained more consistent REA effects (Studdert-Kennedy & Shankweiler, 1970). The CVC-paradigm was then simplified into consonant vowel (CV)-pairs that have become the “standard” paradigm over the years adopted all over the world (see Bryden, 1988, Bradshaw, Burden, & Nettleton, 1986; Springer & Deutsch, 1998; Hugdahl, 1992, 1995). The Bergen DL test was developed by Kenneth Hugdahl at the University in Bergen, Norway and is now used in many laboratories and clinics internationally (Hugdahl, 1995; Hugdahl & Wester, 1992; Hugdahl et al., in press). In this DL variant, the stimuli are CV-syllable pairs made of the six stop consonants already used by Studdert-Kennedy and Shankweiler (1970) together with the common vowel /a/, to provide stimuli pairs of the type /ga-da/, /ka-ba/, etc. The CV-syllables are paired with each other yielding 36 dichotic pairs, including the homonymic pairs which are mostly excluded in the statistical analyses. Only a single pair of syllables is presented on each trial, thus reducing memory load to a minimum compared to the strings of stimuli used in other DL paradigms. All pairs are presented several times in a random order. When applying the three possible attention instruction conditions (non-forced attention, forced-right, forced-left), the total amount of trials are divided into three trial blocks, one for each condition. The syllables are read with constant intonation and intensity, and a mean duration of approximately 350-450 ms. The stimuli are digitized and synchronized for simultaneous onset and offset between the right and left channels. The CV-syllables are presented through headphones to the subjects who were seated in an acoustically shielded room.

Prior to the testing, any differences in hearing acuity between the ears in the subjects are typically tested with standard audiometer screening procedures. The subjects are given standardized instructions to listen carefully to the stimuli and after each presentation to quickly repeat the sound they heard first or best without thinking. An alternative way to the verbal response is asking the subjects to point to the one syllable they have heard among the

six possible answers which are written on a paper or displayed on a computer screen. In the Bergen laboratory, a single response on each trial is typically asked for, although the subjects may sometimes perceive both stimuli presented on a trial.

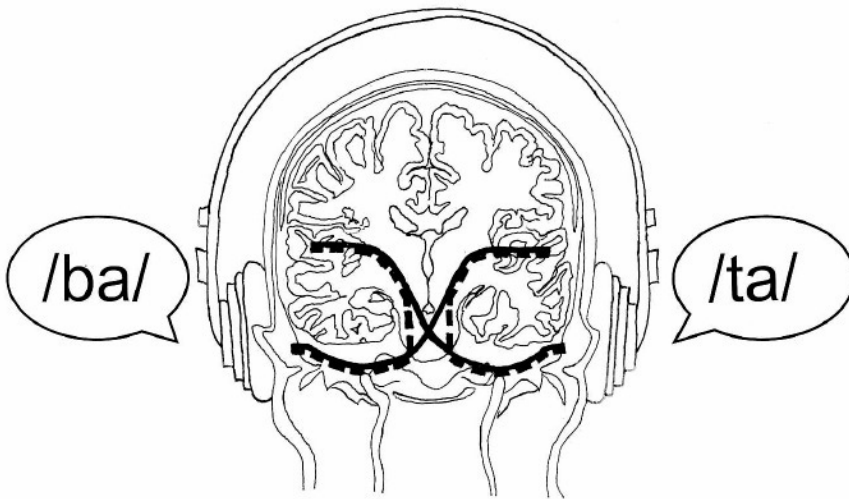
The results from several studies using the Bergen DL test showed in general an REA in approximately 80% of right-handers and in 65% of left-handers (Hugdahl, 1995; Hugdahl & Andersson, 1989; see also Hugdahl, 2005 and Tervaniemi & Hugdahl, 2003). The REA effect is also seen among children down to the age of five years, suggesting that the REA in DL studies is a robust finding. Even though it was repeatedly demonstrated that ear advantages in the Bergen DL procedure are quite consistent across measures for both adults (Hugdahl, 1995; Hugdahl & Hammar, 1997) and children (Andersson & Hugdahl, 1987), its reliability is still a matter of debate for some researchers (e.g. Bethmann, Tempelmann, De Bleser, Scheich, & Brechmann, 2007). The REA in DL has also been validated with several methods, for example with data from the Wada procedure. Using a discriminant analysis, the results revealed a correct classification of DL performance according to the Wada test results in more than 90% of all subjects (Hugdahl, Carlsson, Uvebrant, & Lundervold, 1997; see also Hugdahl & Andersson, 1989). Satisfactory validity of the DL procedure was further confirmed using brain imaging methods (Hugdahl et al., 1999), where neuronal activation to the CV-syllables have been closely mimicked by the performance data. Although the REA to CV-syllables seems to be a robust empirical phenomenon (Hugdahl, 1995), it is however sensitive to different modulatory factors, for example an involuntary attentional bias where a hemisphere-specific ear advantage may be shifted if attention is focused to the ipsilateral ear (Asbjørnsen & Hugdahl, 1995; Mondor & Bryden, 1991). The degree of the REA has also been shown to differ interindividually that may underlie for example several neurocognitive anomalies such as dyslexia or schizophrenia (Tervaniemi & Hugdahl, 2003). The Bergen DL test was used in the present thesis to assess hemispheric asymmetry for phonetic processing in a noisy environment.

## 2.4. Theoretical models of the REA

### 2.4.1. *The structural model*

The probably most generally accepted explanation of the REA is the so-called structural model suggested by Kimura (1967) emphasizing several interacting factors causing the REA. According to Kimura (1967), the REA is a consequence of the functional-anatomic

organization of the central-auditory system, as well as the cerebral representation of language functions. Whereas the two ears project from the cochlear nucleus to the primary auditory cortex in both temporal lobes each, input arriving via the contralateral pathways exhibits a stronger representation at the cortical level and, furthermore, seems to block or suppress ipsilateral signals. The model also assumes that, at least in right-handers, the areas in the left temporal lobe predominantly process phonological stimuli. Thus, material presented to the right ear will have direct access to the contralateral hemisphere and therefore will be more easily detected than material presented to the left ear, which will have to cross the corpus callosum to reach the language-dominant hemisphere (callosal relay model). Similarly, a non-verbal stimulus presented in the left ear has direct access to auditory areas in the right hemisphere. Figure 1 shows a schematic illustration of the structural model.



*Figure 1: Under dichotic listening conditions, left ear stimulus (/ba/) may reach the left hemisphere over the suppressed ipsilateral pathway or over the contralateral pathway to the right hemisphere and then across the corpus callosum. Right ear stimulus (/ta/) gains direct access to the left hemisphere along the contralateral route.*

The structural model has been supported for example in the studies by Sparks and Geschwind (1968), and Milner, Taylor, and Sperry (1968), who reported a near-complete extinction in the left ear channel in commissurotomy patients in a DL test (see also Pollmann, Maertens, von Cramon, Lepsien, & Hugdahl, 2002). Also recent functional imaging studies, using both hemodynamic and electrophysiological methods, have provided evidence for the structural model (e.g. Brancucci et al., 2004; Hugdahl et al., 1999; Jäncke &

Shah, 2002; Mathiak, Hertrich, Lutzenberger, & Ackermann, 2002). However, one weakness in Kimura's model is its pure structural basis, which does not provide an explanation for individual variability and/or cognitive modularity.

#### 2.4.2. *The attentional model*

An alternative view was proposed by Marcel Kinsbourne introducing an additional attentional component (Kinsbourne, 1970, 1973, 1975). He suggested that expectation of incoming verbal material would prime or pre-activate the left hemisphere, and that anticipation of non-verbal material would likewise prime or pre-activate the right hemisphere. Therefore, the REA for verbal material would arise because the verbal stimuli would sensitize the left hemisphere to all incoming stimuli and thus setting up a processing advantage. Similarly, a LEA for non-verbal material would arise because of a pre-activation of the right-hemisphere – not because of suppression of ipsilateral input – leading to an advantage for the left ear stimulus, which was supported by Jäncke (Jäncke, 1994). However, several studies have provided evidence that attentional biases may not be the sole determinant of DL effects (Goodglass & Calderon, 1977; Bryden & Murray, 1985), but may contribute to the magnitude of the REA (MacKain, Studdert-Kennedy, Spieker, & Stern, 1983).

### 3. Functional magnetic resonance imaging

With the emergence of functional neuroimaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), an indirect observation of the neuronal activity in specific brain regions became possible and a new scientific discipline known as cognitive neuroscience was created (Gazzaniga, 2004). PET and fMRI result in visualization of regional changes in brain metabolism that can be used to explore the functional organization of the brain in vivo and thus can complement traditional neuropsychological findings by providing data at the neuronal level. Coupled with behavioral data, functional neuroimaging methods show great potential to enhance our understanding of how cognitive processes are implemented in the brain (Ingvar & Petersson, 2000; Raichle & Mintun, 2006; Detre & Floyd, 2001; Huettel, Song, & McCarthy, 2004). To elucidate the neuronal mechanisms that underlie background noise influences on asymmetrical speech perception assessed with the DL procedure, fMRI was used in Report III.

#### 3.1. MRI – Definition and basic principles

MRI is an abbreviation for magnetic resonance imaging, and is a medical imaging technology that uses strong magnetic fields generated by an MRI scanner (Figure 2) to create images of biological structures, especially of soft tissues like the brain. Figure 2 shows an example of an MRI scanner.



*Figure 2: Shown is a Signa series MRI scanner from General Electric, which uses a closed-bore design, in which the person is placed into the middle of the bore.*

Present standard clinical MR imaging is based on proton imaging, the positively charged nucleus of hydrogen atoms. Since 75% of the human body consists of water, it is hydrogen which is the most abundant element in the body. Thus, the signal is derived from the proton resonance of hydrogen nuclei in tissue and organs (English & Moore, 1995). Normally, the orientations of the proton spins, i.e. the magnetic moment of the nucleus, are randomly distributed, but under the influence of an external magnetic field, they align and precess along the axis of the external magnetic field (Chavhan, 2007). The frequency with which the protons are precessing is given by the strength of the external magnetic field (Larmor frequency). By using additional gradient fields, the effective strength of the magnetic field is different at different locations. Thereby, the Larmor frequency can be varied during the MRI measurement. In addition, the patient is repeatedly exposed to a radiofrequency (RF)-pulse that matches the specific Larmor frequency only of those protons that are at a specific position in the gradient field. The protons absorb the energy (resonance absorption), causing them to momentarily align against the magnetic field in a high-energy state. Once the RF-pulse stops, the protons realign again, they emit the energy at the same frequency and return to their original equilibrium orientation (relaxation). The time they need to reach the original equilibrium state is tissue dependent. During the relaxation process, the MR signal is induced in the receiver coil and analyzed by Fourier transformation in order to locate spatially the data acquired and to produce MR images. The signal level, i.e. the image contrast is determined by the proton density and the relaxation properties of the tissue (Krause, 2002).

#### *Functional magnetic resonance imaging (fMRI)*

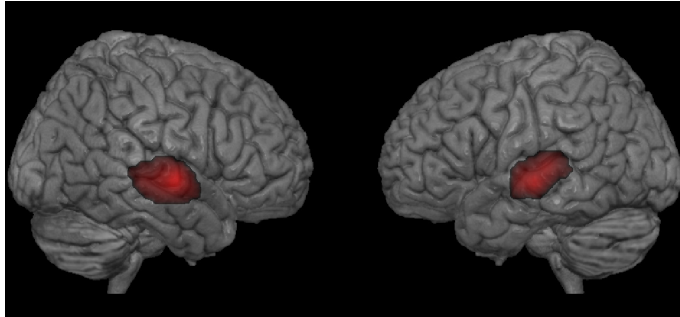
fMRI – the functional variant of MRI scanning – uses the same basic physics principles as conventional MRI, but uses in addition the different magnetic properties of oxygenated and de-oxygenated blood in order to measure brain metabolism and neuronal function. It has been gaining increasing popularity over other functional imaging methods especially because it is non-invasive, allows to measure brain functions in healthy subjects of all ages repeatedly, and over a substantial period of time, while it does not require exposure to ionizing radiation. Additionally, it is nowadays widely available not only in hospitals but also in many research laboratories around the world. Furthermore, fMRI offers reasonable temporal and a high spatial resolution with whole-brain coverage that makes this method outstanding in functional neuroimaging. Even though it was introduced only around 15 years

ago, nowadays fMRI is used in both clinical and research settings from psychology to biomedical engineering.

The standard fMRI technique is based on the BOLD (blood oxygen level dependent) contrast that (in-)directly monitors regional changes in blood oxygen level as a consequence of neuronal provocation. Beginning remarkably soon after the first demonstrations in humans (Bandettini, Wong, Hinks, Tikofsky, & Hyde, 1992; Kwong et al., 1992; Ogawa et al., 1992) fMRI-BOLD contrast has come to dominate the functional neuroimaging field. The BOLD contrast reflects the difference in magnetic properties between oxygenated and deoxygenated blood, whereas it not only depends on hemoglobin oxygenation but also on blood flow and blood volume, reflecting a complex interaction controlled by several parameters (Logothetis, 2002). Although the mechanisms behind the neurovascular coupling are not fully understood (see Logothetis, 2008; Logothetis & Wandell, 2004), local neuronal activation causes changes in the relative concentration of oxygenated and deoxygenated blood. Oxygenated and deoxygenated hemoglobin have different magnetic properties: In contrast to oxygenated hemoglobin which is diamagnetic, minimally affecting the magnetic field, deoxyhemoglobin is paramagnetic and influences the magnetic field, producing measurable changes in the MR signal (Logothetis, 2008; Ogawa, Lee, Kay, & Tank, 1990). Regarding the temporal characteristics of the BOLD response, the signal increases in amplitude at about 2 s following the onset of the neuronal stimulation, growing to a maximum value (i.e. peak). After reaching its peak, the signal decreases to a level below baseline (i.e. undershoot) at about 4-6 s due to the combination of reduced blood flow and increased blood volume. As blood volume returns to normal level, the BOLD signal will similarly increase to baseline (Huettel et al., 2004). This change in MR signal following neuronal activation is also called the hemodynamic response function. Activation maps (Figure 3) are produced that typically depict the average level of engagement, i.e. neuronal brain activation of different regions in the brain, during a specific task or in response to specific experimental conditions relative to a baseline or control condition. It is important to note that fMRI is only a relative measure, i.e. only the change from one condition to another condition can be inferred, but not a 'total amount' of activation. The activation patterns are therefore usually reflecting relative changes in the blood oxygenation. These activation patterns may be compared between conditions or between groups of subjects to evaluate the relative magnitudes of different responses. Thus, fMRI allows the researcher to draw inferences about the underlying neuronal activation from BOLD



data and how different brain regions may support different sensory, motor, emotional, and cognitive processes. Figure 3 shows an example of a functional map of the brain.



*Figure 3: A statistical map of fMRI data displayed on a background anatomical MR image. Areas of statistically activation are shown in color, with the intensity of the color corresponding to the significant value.*

Echo-planar imaging (EPI), an ultra high-speed pulse sequence, and its variants have become the methods of choice for the majority of fMRI studies. With an EPI sequence, a complete slice is acquired in less than 100 ms and is therefore known as a “snapshot” imaging method (Mansfield et al., 1990). To acquire a whole brain volume that would typically contain 20-30 slices would thus take about 2-3 s. EPI sequences allow functional imaging experiments to be performed with a higher spatial resolution compared to for example PET, electroencephalography (EEG), and event-related potentials (ERPs). Although temporal resolution is not close to the ms resolution of EEG and ERPs the spatiotemporal features of EPI are unique in functional neuroimaging (Eichele et al., 2005; Turner, Howseman, Rees, Josephs, & Friston, 1998).

### 3.2. Experimental fMRI designs

The block-design is the traditional type and the most common used experimental design in fMRI. In a block-design, the same type of stimuli is presented sequentially within a block of typically 20-40 s, and two or more blocks of different experimental conditions are then alternated for an extended time-period. The most common block-design alternates between two conditions (experimental block vs. control block) for the duration of the experiment, allowing identification of voxels showing differential activation as a function of the independent variable, i.e. the difference in BOLD signal between the conditions (alternating

design). A rest condition, containing no task requirements, may be additionally introduced between the alternating blocks in order to measure activation independent to each condition (control block-design). Blocks that represent the same condition are then grouped together, and are compared using statistical inference, or correlation tests. Block-designs are very effective, resulting in large signal changes, because events are concentrated within task blocks. However, randomization of stimulus types is not possible within a block, the type of stimulus may become very predictable, thus participants may become aware of the order of the events (Donaldson & Buckner, 2001). In addition, block-designs do not allow to measure the shape of the hemodynamic response to single events (Huettel et al., 2004).

Event-related designs constitute the second major class of fMRI experimental designs and involve modelling changes in the BOLD signal associated with individual trials, as opposed to block of trials that are grouped together. Event-related studies measure transient changes in brain activation associated with discrete stimuli, they allow for randomized presentations of different stimulus categories within a single scanning session, each event separated in time from the previous event (inter-stimulus interval). The inter-stimulus intervals may occur at regular intervals (periodic event-related design), or may be randomized over some range (jittered design). The event-related design also allows for the examination of individual trials, and the time course and shape of the hemodynamic response can be estimated. Furthermore, presenting different trials within a single session may minimize possible confounds such as anticipation, habituation, and strategy effects (e.g. Rosen, Buckner, & Dale, 1998). In general, event-related designs have a good estimation power, i.e. precise characterization of the timing and the shape of the BOLD response, but poor detection power. However, the power can be increased either by introducing a latency jitter (Dale, 1999) or by inclusion of null events (Friston, Zarahn, Josephs, Henson, & Dale, 1999).

A fundamental complication in auditory fMRI studies, independent of the selected experimental design, is the intense scanner noise during high-speed image acquisitions (<100 dB) resulting from mechanical forces created by the switching of the gradient coils every time the MR signal is read out. This may lead to both direct and indirect confounding of the BOLD signal of interest (Moelker & Pattynama, 2003), for example confounding BOLD responses evoked by the noise may be induced and / or the scanner noise may act as a perceptual mask over the auditory stimuli. A general method to minimize the masking problem has been to interleave a silent period, the so-called silent “gap” between the acquisitions of each image

volume in which the auditory stimuli are presented (Amaro et al., 2002; Hall et al., 1999). This type of acquisition has been described as sparse sampling (Hall et al., 1999).

An event-related sparse sampling experimental design was chosen in Report III with the auditory stimuli presented and the verbal responses collected in silent gaps to prevent the stimuli from being masked by the scanner noise (i.e. to ensure that the measured activation in the auditory cortex is uncontaminated by its response to the preceding burst of scanner noise). In addition, variable jitter intervals are introduced to avoid habituation and anticipatory effects, and to permit sampling at different time-points on the hemodynamic response function curve to optimally characterize the BOLD response.

### 3.3. fMRI pre-processing and data analysis

The analysis of fMRI data typically entails multiple stages of data pre-processing, i.e. a series of computational procedures, following image reconstruction but prior statistical analysis (Huettel et al., 2004). The purpose of the pre-processing is to reduce unwanted variability in the data, to condition the data in order to maximize the sensitivity of later statistical analysis, and to improve the statistical validity (Smith, 2004). The basic steps in pre-processing at the single-subject level commonly include slice time correction as a first step to adjust the data so that it appears that all voxels within one volume had been collected at exactly one point in time. A second step corrects for head motion by realigning to a common reference. Then spatial normalization is performed by changing the orientation, size and shape of the brains of the individual subjects to match those of a standard brain (Ashburner & Friston, 2003), followed by spatial co-registration, i.e. the alignment of scans from different modalities. Spatial smoothing as a next step removes the high spatial frequencies in the fMRI signal to improve the signal-to-noise-ratio, smoothing also removes small frequency differences to make comparisons across subjects easier, and makes the data more normally distributed to satisfy the requirements for applying Gaussian Field Theory. Smoothing is generally performed by convolving the 3D volume with a 3D Gaussian kernel. Global intensity normalization is done in a further step to reduce the effect of global changes in intensity between volumes by re-scaling the intensities to a common mean intensity value (Kiebel & Holmes, 2003). Because time series from each voxel contains low frequency drifts and high frequency noise that may hide activation, temporal filtering or smoothing, i.e. the removal of certain unwanted temporal frequencies from the dataset, is implemented as a final step.

After pre-processing, fMRI data has to be statistically analyzed to determine which voxels are activated by the stimulation. There are different approaches to obtain activation maps, but one of the primary statistical tools to examine changes in brain activation is Statistical Parametric Mapping (SPM). SPM uses a general linear model (GLM), i.e. multilinear regression, to transform the fMRI data into statistical maps of task-specific, voxel-based image differences in the magnitude of the BOLD signal. First, GLM sets up a model composed of several different components specified in the design matrix. Subsequently, the model has to be fit to the observed data, i.e. the parameters of the model must be estimated. As a next step, a  $t$ -test will be used to determine for each voxel separately whether a specific linear combination of estimated parameters is significantly different from zero (Kiebel & Holmes, 2003), i.e. which parts of the brain are activated at a given level of significance. The result is a  $t$ -score for each voxel and for each linear combination of predictor variables, which is then converted to a  $Z$ -score. In order to infer on the group level, a ‘second-level’ or ‘random effects’ analysis has to be performed. In such a second-level analysis, a variety of statistics can be applied, mainly one- and two-sample  $t$ -tests or analyses of variance (ANOVA). Since all described data analyses are done voxel-by-voxel-wise, the number of performed  $t$ -tests is reasonable high, increasing the number of false positives. The standard strategy to control the problem of multiple testing is to consider the family-wise error rate (FWE), i.e. the probability of at least one false positive on any voxel in the image (Logan & Rowe, 2004). The simplest way to control the FWE is through the Bonferroni correction. However, Bonferroni correction is only rarely adopted because it overestimates the number of independent statistical tests (Huettel et al., 2004). Hence, the corrected thresholds are too conservative since most functional imaging data have some degree of spatial correlation (Kilner, Kiebel, & Friston, 2005). Therefore, Gaussian random field methods can be used that account for the dependence in the data, however, they are suitable only for smoothed data (Genovese, Lazar, & Nichols, 2002). Alternatively, a more liberal correction technique can be applied: The false discovery rate (FDR) which is the expected proportion of false positives to total positives (Logan & Rowe, 2004).

## 4. Background noise

### 4.1. Definition of background noise

Background noise is an unwanted sound or set of sounds that obscures a signal or a sound being monitored (Ouis, 2001). Since it is not possible to classify sounds as noise on the unique basis of their physical characteristics, it is generally agreed that noise is an audible acoustic phenomenon that may adversely affect people (Kryter, 1999; Muzet, 2007). Examples of common background noises are environmental noises displaying bioacoustic noise, like animal calls, human sounds, like people talking, or machine-created sounds, like traffic noise and air-conditioning. Noise constitutes one of the most widespread public health threats and hazardous type of pollution in industrialized countries (Passchier-Vermeer & Passchier, 2000), with especially human sounds and machine-created sounds being an ever-increasing problem in society. Their detrimental effects on human health and psyche pose a growing problem in modern society (Kujala et al., 2004).

### 4.2. Effects of noise on cognition

Background noise is often discussed in terms of mental costs, and impaired brain dynamics. Many studies of stress in general and noise in particular have focused on task efficiency and have observed impacts related to attention and memory functions.

There have been two major theoretical constructs to explain the effects of stress in general (including noise) on cognitive performance: The arousal model states that the effects may be due to the general level of activation (or arousal / alertness) of the physiological systems underlying behavior (Broadbent, 1963), whereas the information overload model emphasizes the impact of stressors in general on cognitive capacity (e.g. Cohen, 1978).

The observed effects of noise on attention in particular can be explained by several other theoretical models, e.g. changes in performance strategies, attention reallocation or selectivity, distraction, or masking of acoustic cues or inner speech (see overview in Cohen, Evans, Stokols, & Krantz, 1986; Jones, 1990; Smith, 1991).

Effects of noise have also been found in tasks requiring different memory systems (e.g. see overview in Cohen et al., 1986; Hygge, Boman, & Enmarker, 2003), where a great deal of attention has been focused upon a phenomenon referred to as the “irrelevant sound

effect” (ISE) (Beaman & Jones, 1997, for a review see Beaman, 2005). Different theoretical accounts have been proposed to explain the ISE (e.g. Baddeley, 1986, 2002; Broadbent, 1984; Poulton, 1977), e.g. that the effect may be due to a conflict based on similarity in process between rehearsal of the relevant sequence in short-term memory and the perceptual organization of the irrelevant sound (Jones, 1999; Jones & Macken, 1995; see also Salamé & Baddeley, 1982).

Thus, noise has a definite effect on cognitive performance, but the precise nature of the effect depends on the cognitive demands of the task being performed and on specific task parameters (Smith, 1991). Furthermore, the effect of background noise also depends on the different noise parameters, which will be elaborated in Section 4.4.

### 4.3. Effects of noise on speech perception

Since understanding the perceptibility of speech signals is of great significance for the quality of human life, a great deal of research has been particularly focusing on the perception of *speech* in noise. In everyday listening conditions, speech perception almost never occurs in silence. Rather, speech in real-world situations mostly occurs in the presence of various kinds of distracter background noises that may degrade the speech signal of interest. The relationship between noise and speech perception is quite complex (often referred to as “cocktail party problem”, Section 4.3.1.) and various fields of research such as psychophysics, psychoacoustics, psycholinguistics, clinical psychology etc. have investigated the effects of noise on different aspects of speech perception using tasks for example on speech intelligibility, recognition, identification, and discrimination. For the present work, studies examining the effects of noise on underlying brain processes are in focus, particularly on the asymmetry of speech perception outlined in Section 4.3.2.

#### 4.3.1. *The cocktail party problem*

Hearing in complex acoustic environments is often exemplified by the “cocktail party problem” (Cherry, 1953). The cocktail party phenomenon has been examined in psychophysics from the viewpoint of sound source segregation; The auditory system is capable of solving this cocktail party problem by the so-called “auditory scene analysis”, which enables the brain to separate the complex sound source “mixture” into distinct acoustic streams (Bregman, 1990). The cocktail party situation has turned out to be a highly complex

listening situation, involving different phenomena, including acoustic phenomena, such as perceptual (or informational) masking and associated (speech) segregation effects, energetic masking, binaural unmasking, but also attention (Bronkhorst, 2000).

#### 4.3.2. *Effects of noise on cortical organization and asymmetry of speech perception*

The effects of noise on cortical mechanisms underlying speech perception have mainly been investigated using electrophysiological techniques. Studies using cortical event-related potentials (ERPs) to speech sounds generally demonstrated that discriminating speech in noise resulted in slower and less efficient processing – often accompanied by a decrease in behavioral performance. However, noise is found to affect different ERP components (representing different processing levels of the auditory system) in a different manner (Kaplan-Neeman, Kishon-Rabin, Henkin, & Muchnik, 2006; Martin, Kurtzberg, & Stapells, 1999; Martin & Stapells, 2005). Kaplan-Neeman et al. (2006) for example found reduced initial auditory processing which was suggested to be due to changes in physical characteristics of the stimuli in noise while higher-order processing was found to be enhanced because the masking noise may lead to an increase in listeners uncertainty regarding identification (Kaplan-Neeman et al., 2006). Muller-Gass, Marcoux, Logan, & Campbell (2001) and Kozou and colleagues (2005), particularly investigated the effects of noise (varying noise intensity in the study by Muller-Gass et al., and varying the type of noise in the study by Kozou et al.) on pre-attentive auditory processing as indexed by mismatch negativity (MMN). Muller-Gass et al. found the MMN and behavioral performance to be affected, especially by high intensity noise, suggesting that both pre-attentive and attentive speech discrimination deteriorate following a reduction in audibility (Muller-Gass et al., 2001). Accordingly, Kozou et al. found the MMN to be reduced, but differently dependent on the type of noise. In contrast to Muller-Gass et al., behavioral performance remained stable, which was attributed to attentive top-down mechanisms that may compensate for the noise effects on pre-attentive processes (Kozou et al., 2005).

Hemodynamic neuroimaging methods in contrast have been used far less to investigate neuronal response to background noise; Salvi et al. (2002) used PET imaging to identify brain regions activated during speech in ‘babble’ and speech in quiet. The results showed a small decrease in activation level (but increase in extent of activation) in temporal areas, but also an increase in activation particularly in cerebellum and thalamus, suggested to reflect greater cognitive, arousal and attentional demands in noisy listening situations. In an

fMRI study by Hwang and colleagues (Hwang, Li, Wu, Chen, & Liu, 2007) who studied speech comprehension in white noise in elderly and young subjects, the extent of activation to speech particularly in the left STG was found to decrease in noise compared to when speech was listened to in quiet, especially in elderly. There are various studies focusing particularly on the effects of noise produced by the gradient system of the MRI scanner on activation in auditory cortex to speech stimuli (e.g. Gaab, Gabrieli, & Glover, 2007a; Gaab, Gabrieli, & Glover, 2007b; Shah, Jäncke, Grosse-Ruyken, & Müller-Gärtner, 1999). In general, decreased performance due to reduced audibility and modulated central top-down mechanisms, as well as activation provoked by the noise that masks, i.e. decreases stimulus- or task-driven signal intensities within auditory areas has been documented (Gaab et al., 2007a, see also Amaro et al., 2002 for a review).

Interestingly, studies comparing differences in brain activation between the hemispheres have shown that background noise alters speech processing in the left and right hemisphere differently. In a magnetoencephalography (MEG) study, Shtyrov and colleagues (1998) found that when speech was presented in silence, the magnetic MMN (MMNm) was predominately generated in the left auditory cortex, whereas in background noise, the MMNm dipoles diminished in the left and increased in amplitude in the right hemisphere. In a subsequent study, Shtyrov and colleagues (1999) showed lateralization effects even in early components (P1m, P2m). They showed that noise affects the left and right brain responses differently, with a decreased involvement of the left hemisphere in noise while, in case of P2m, that of the right hemisphere increases, suggesting that in real-life listening situations involving noise, right auditory cortex structures are additionally recruited. Hermann, Oertel, Wang, Maess, & Friederici (2000) also found hemisphere specific effects of noise for primary auditory processes, with decreased magnetic responses only over the right hemisphere in noise. Activation shifts from the left to the right hemisphere when noise is present during speech discrimination was also seen in a study by Muller-Gass et al. (2001) investigating the MMN. Speech processing was also suggested to be reorganized in workers exposed to long-term occupational noise (Brattico et al., 2005; Kujala et al., 2004). However, Kozou and colleagues (2005) studied the effect of different types of noises on the central auditory processing by means of MMN and found no hemispheric differences in noise conditions (see also Martin & Stapells, 2005). In an fMRI-study by Hwang, Wu, Chen, and Liu (2006), noise was shown to have different effects on the two hemispheres during speech listening:



Auditory-associated cortices were more affected in the left hemisphere than in the right (see also Hwang et al., 2007).

These results are in line with earlier behavioral findings demonstrating a modulated REA in dichotic listening due to noise, already indirectly suggesting that background noise cause changes in the basic functional asymmetry of central speech processing (e.g. Godfrey, 1974; Koroleva & Shurgaya, 1997; Weiss & House, 1973; see also Shtyrov et al., 1998 for further references). Although Cullen, Thompson, Hughes, Berlin, and Samson (1974) found no change in REA in white noise, Godfrey (1974) for example reported an increasing REA when white noise was additionally presented. Moreover, Koroleva and Shurgaya (1997) demonstrated a stronger decrease in the number of correct reports from the right ear compared to the left ear in noise that may be considered as a sign of change regarding the lateralized speech perception mechanisms.

#### 4.4. Noise parameters

##### 4.4.1. *Type of noise*

Artificially generated continuous white noise has been widely used in behavioral, electrophysiological and imaging experiments to study the effects of environmental stress (noise as the stressor) on humans. Particularly, in studies on speech intelligibility and recognition white noise has been the noise most frequently used to mask the speech signal (Rhebergen, Versfeld, & Dreschler, 2008). White noise was also used in studies investigating speech identification, i.e. discrimination (Jiang, Chen, & Alwan, 2006; Kaplan-Neeman et al., 2006; Kozou et al., 2005), central auditory processing (Hwang et al., 2006) as well as the asymmetry of speech perception (e.g. Godfrey, 1974; Koroleva & Shurgaja, 1997; Shtyrov et al., 1998). However, since in ordinary life people are seldom exposed to white noise and since the effects of wide band noise have been shown not to reflect the auditory perceptual problems encountered in everyday listening situations (Kozou et al., 2005), the experimental use of everyday-noise, much more complex in the spectro-temporal domain compared to broad-band white noise, is of high importance in order to increase ‘ecological validity’ of the settings.

Transportation noise (road traffic, railway, and air traffic noise) is said to be the main source of noise (Ouis, 2001) and most widespread source of noise complaints (Hygge, 2003), thus, it has been addressed in a variety of studies on memory, attention, learning and reading

(e.g. Clark, et al., 2006; Enmarker, 2004; Evans & Maxwell, 1997; Hygge, Evans, & Bullinger, 2002; Hygge et al., 2003). Until today, only a few studies have investigated the effects – acute or chronic – of traffic noise on speech perception by means of behavioral as well as electrophysiological measurements (e.g. Cohen, 1973; Hygge et al., 2002; Klatte, Meis, Sukowski, & Schick, 2007; Kozou et al., 2005). Short-term noise effects on speech intelligibility were found by Klatte et al. (2007) and have been attributed to physical masking. In an ERP-study by Kozou and colleagues (2005), acute traffic noise affected only the cerebral (as indexed by the MMN) but not the behavioral discrimination of speech stimuli. Attentive top-down processes have been suggested to compensate for the noise effects on early auditory processing (Kozou et al., 2005).

Another noise parameter that is also a common disturbance for instance in schools and working environments is verbal or conversational noise, i.e. speech or ‘babble’ (Banbury & Berry, 2005). Although speech noise is characterized by much higher face validity than white noise, it is less common used in experimental settings because of its lower test reliability due to the highly modulated temporal and spectral pattern of the speech sound (Larsby & Arlinger, 1994). Besides the well-studied effects of unattended (i.e. irrelevant) speech on memory performance (e.g. Hygge et al., 2003; Jones, Alford, Macken, Banbury, & Tremblay, 2000; Klatte et al., 2007), different aspects of speech perception, such as speech identification and recognition (Cutler, Weber, Smits, & Cooper, 2004; Klatte et al., 2007; Larsby & Arlinger, 1994; Sperry, Wiley, & Chial, 1997; Takata & Nábělek, 1990), behavioral and cerebral speech discrimination have also been shown to be affected by ‘babble’ noise (Kozou et al., 2005; Prosser, Turrini, & Arslan, 1991). Speech noise is acoustically complex, and research findings regarding its effects on speech perception vary because of the variety of competitors (number of talkers constituting the ‘babble’; Simpson & Cooke, 2005), the informational content it contains (Sperry et al., 1997; but see also Dirks & Bower, 1969), the particular test of speech perception, and the test material used. The effects of ‘babble’ on speech perception have therefore been suggested to result from different factors or an interaction of those: peripheral mechanisms, additional central mechanisms including changes in signal processing in the brainstem and higher levels of cognitive functions such as information processing, attention, memory, and distraction (Prosser et al., 1991).

To directly examine and compare the differential effects of various types of noises it is necessary to include different noises in the same experiment. This approach has been often adopted in studies investigating noise effects on memory and attention (e.g. Baker & Holding,

1993; Hygge, 2003), but only a few studies have directly compared the relative effects of different types of background noise in speech perception experiments, also with conflicting results. For example, Prosser et al. (1991) investigated the effects of speech, cocktail party, traffic noise and continuous discourse on speech discrimination. Speech and cocktail party noise were found to be more detrimental than traffic noise and continuous discourse. Klatte and colleagues (2007) observed that traffic noise tended to be more detrimental in a word identification task compared to speech noise. In an ERP-study, Kozou et al. (2005) found that different noise types (babble, industrial, traffic, and wideband noise) had a differential effect on cerebral speech discrimination to speech (as indexed by MMN) compared to silence, but with traffic revealing a stronger effect than babble, while wideband noise was observed to have the smallest effect. In contrast, Tun and Wingfield (1999) found white noise to have the largest effect compared to one competing speaker, two competing speaker and multitalker babble.

Because previous studies have varied in so many ways – including the use of different tasks, different types of speech materials, signal-to-noise ratios, i.e. intensity levels, etc. – it remains difficult to draw conclusions about the effects of different types of noise on speech perception. However, it has been suggested, that in general the differential effects of noise depend on the continuity, i.e. stationarity of the distracter sound since masking was shown to be more intense if the noise is continuous compared to fluctuating with regard for instance to the frequency spectrum and amplitude modulation (Cooke, 2006; Prosser et al., 1991; Scott, Rosen, Wickham, & Wise, 2004; Tun & Wingfield, 1999). This relationship may moreover be modulated by the informational content of the noise that may lead to linguistic uncertainty and the involvement of higher cognitive functions (e.g. attention) (Garstecki & Mulac, 1974; Scott et al., 2004; but see also Dirks & Bower, 1969).

Since it has been shown that noise influence the left and right hemisphere in a different manner, and since it was repeatedly shown that different types of background noise have differential effects on various aspects of speech perception, it may be obvious to suspect that lateralized speech processing may also vary with respect to the type of background noise. To our knowledge, there are no previous studies comparing the effects of different kinds of ‘ecological valid’ everyday background noises such as babble and traffic on the asymmetry of speech perception.

#### 4.4.2. *Intensity level of noise*

Intensity level has always been a variable of primary interest in research on noise effects. Early research on auditory speech perception has primarily been focused on psychoacoustic mechanisms, although cognitive factors such as attention have been invoked when interpreting the findings. Thus, dependent on the type of noise used in the experiments (e.g. white noise, different kinds of speech), modulations of performance (listening to speech) due to noise level variation have been explained by energetic or/and informational masking effects. For example white noise was shown to disrupt performance largely as a function of its intensity since white noise involve purely energetic masking effects (due to spectral overlap between the speech signal and the white noise) that have been shown to be level-dependent (articulation index theory; French & Steinberg, 1947). Thus, the lower the signal-to-noise ratio, the greater the masking of the signal (e.g. Kaplan-Neeman et al., 2006; Muller-Gass et al., 2001). Additional higher-level informational masking occurs when for instance signal and noise are very similar (Brungart, 2001; Festen & Plomp, 1990) or when the noise contains informational, i.e. semantic content – as in speech noise – that may lead to perceptual competition with the target speech and hence resulting in attention reallocation or distraction (Dirks & Bower, 1969). In contrast to energetic masking, informational masking is characterized by unusually shallow slopes of growth of speech recognition performance with increasing signal-to-noise ratio, i.e. plateaus/dips between -10 and 0 dB signal-to-noise ratio. This finding points to the relative level-independency in those regions because here the listener can segregate by level and extract information from the softer talker (Brungart, 2001; Dirks & Bower, 1969; Freyman, Helfer, McCall, & Clifton, 1999). Experiments using speech noise as masker resulted however in ambiguous findings, primarily because of the number of masking talkers (e.g. Brungart, 2001; Freyman et al., 1999 for level effects of a single talker as masker; Cutler et al., 2004; Freyman, Balakrishnan, & Helfer, 2004 for level effects of multitalker babble). To our knowledge there has been no study on auditory speech perception using intensity modulation of other noises such as traffic noise.

Noise level effects may alternatively be interpreted in terms of arousal. Noise was shown to produce arousal (Broadbent, 1971; but see also Hygge et al., 2003), which in turn interacts with performance: arousal will help performance as long as it is not excessive; too much arousal leads to decreased performance (Yerkes & Dodson, 1908). It may be hypothesized that the level of arousal may be related to the level of the noise: the louder the noise, the higher the level of arousal that may become a negative influence when reaching a level beyond that necessary for optimal performance.

There are only a few studies directly comparing the level dependency effect of different background noise within the same experiment. Scott et al. (2004) varied the intensity of both white noise and a single-talker speech noise to compare their effects on speech comprehension. The authors found speech comprehension to be dependent upon signal-to-noise ratio to a greater degree for the white noise than for the speech noise.

However, a direct comparison of the intensity effects of the most obvious everyday background noises on speech perception has been neglected, thus, in study II we used traffic and speech background noise at varying intensity levels in order to directly compare the intensity effects of 'ecologically valid' background noises on speech perception.

Previous studies have mainly focused on modulation of overall behavior performance due to noise level variation, whereas little research has been done on the effects of intensity regarding hemispheric differences (Muller-Gass et al., 2001; Shtyrov et al., 1998), and especially regarding lateralization of auditory speech processing (Cullen et al., 1974; Godfrey, 1974; Weiss & House, 1973). Increasing the intensity of a white noise masker that was presented in a dichotic listening task to investigate lateralized speech processing was in general shown to result in reduced overall intelligibility due to masking effects, whereas regarding ear advantage, findings were more ambiguous. Cullen and colleagues (1974) for example showed the ear advantage not to be affected by level variation.

Since the above experiments only used white noise in order to study level differences on the lateralization of auditory speech processing, there is no current knowledge regarding how different types of everyday background noise may interact with varying intensity levels. In Report II, the intensity of babble and traffic background noise was varied between 50-65 dB in steps of 5 dB to extend previous findings, and to make the experimental situation more ecologically valid and closer to the problems encountered by people in everyday life, while keeping experimental control.

## 5. Aims and research questions

As reviewed in the sections above, many researchers have studied noise effects on speech perception, but only a few studies have been concerned with effects on the *asymmetry* of speech perception on the basis of single hemisphere involvement. In addition, the focus of previous investigations was mainly on the effects of random undifferentiated white noise – and if more ecologically valid background noises were used, their effects have rarely been compared to each other. Although not always consciously perceived, day-to-day background noise varies in intensity that may influence speech perception, i.e. the speech signal to be shadowed, but modulation of intensity was for the most part disregarded in previous noise research.

Thus, the aim of the present thesis was to investigate the effect of background noise on brain asymmetry for speech perception, operationalized by performance in the Bergen DL test, specified by three research questions:

1. A first research question concerned the effects of different types of background noise on the asymmetry of speech perception. Thus, the present thesis involved two different ecologically valid noises which are usually present in a day-to-day environment: conversational, i.e. ‘babble’, background noise and traffic background noise.
2. A second research question concerned the effects of varying the intensity of the different background noises. Thus, the babble and traffic background noise were presented at different intensity levels in the present thesis, but only such that the speech signal was still intelligible.
3. A third research question concerned the neuronal mechanisms which may underlie the effect of different background noises on asymmetrical speech perception in a dichotic listening task. Thus, fMRI was used to investigate activation patterns in the human brain, especially in speech processing areas that would be activated in dichotic listening and modulated by different noisy backgrounds.

## 6. Summary of Reports I-III

### 6.1. Report I

To examine the effects of different common environmental noises on the behavioral asymmetry of speech perception, six different CV-syllables (/ba/, /da/, /ga/, /pa/, /ta/) were presented dichotically resulting in 30 different CV-syllable combinations (omitting the six homonymic pairs). The DL stimuli were presented either with no background noise (i.e. baseline condition) or with traffic (= background noise traffic, BNT condition) vs. 'babble' background noise (= background noise conversation, BNC condition). The BNC consisted of multi-talker babble which was recorded in two stages. First, eight short conversations between two persons were separately recorded, each consisting of a male and a female native Norwegian speaker. The speakers talked one at a time, immediately resuming the conversation whenever one of them stopped speaking. In the second stage, the eight separate recordings were mixed and overlaid to provide a single sound-file where eight voices were "speaking simultaneously". The traffic background noise (BNT) was originally recorded at a busy traffic intersection in the city center of Bergen, Norway. As for the recordings of the BNC background noise, the recording of the BNT background noise originally consisted of eight different recordings that were overlaid to obtain a mixed sound that had a similar frequency distribution as the composition of the averaged 'babble' sound. By averaging the traffic noise in the same way as the 'babble' sound, unique characteristics (such as a honking car) in the single recordings were less prominent in order to not attract attention when listening. As in the case of the 'babble' background noise, a single sound-file was obtained by overlaying the recordings. It was verified that the intensity distribution across the frequency range was the same for both the BNC and BNT noise.

Both the CV-stimuli and the background noises were presented at approximately 60 dB ( $L_{Aeq}$ , the A-weighted equivalent continuous sound level). The participants were instructed to concentrate on the speech stimuli only, not to pay attention to the background noises. They were further instructed to orally respond with the CV-syllable they heard first or best on each trial.

For each participant and condition the number of correct reports from the right and left ear and an individual laterality index (LI) score was computed. To statistically analyze the

data repeated measures analyses of variance (ANOVA) were conducted. Planned contrasts were calculated for post-hoc analyses.

A significant REA was found for the baseline condition and also for both background noise conditions. However, the simultaneous presentation of background noise led to a decrease in REA. The modulated REA was shown to result from a decrement in performance for the right ear stimulus and an increase in performance for the left ear stimulus, especially for the BNT compared to the BNC condition (Figure 4). These results are discussed in terms of a two-factor alertness-attentional model.

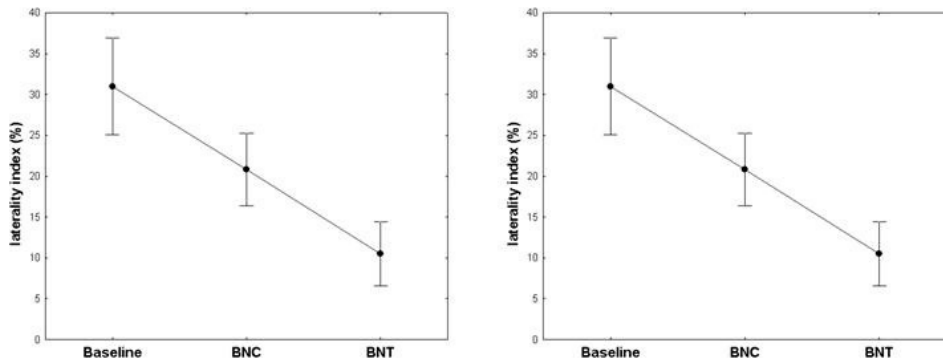


Figure 4: Mean left ear and right ear correct reports (%) (left) and mean laterality index scores (right) for the three different background noise conditions. Vertical bars indicate 0.95 confidence intervals.

## 6.2. Report II

In the second experiment, the focus was on whether different intensity levels of background noise would have a modulating effect on the REA in dichotic listening. Thus, the traffic and babble background noise already used in Report I, was now varied in intensity between 50-65 dB in steps of 5 dB. The CV-stimuli in the DL task remained the same as in Report I. Experiment II included three conditions: CV-syllable pairs with BNC at four different intensity levels (50, 55, 60, and 65 dB), CV-syllable pairs with BNT at four different intensity levels (50, 55, 60, and 65 dB), and an additional condition with no background noise. The number of correct reports from the right and left ear were calculated for each participant and experimental condition and analyzed in a repeated-measures ANOVA. Tukey's HSD-test was



used for post hoc analyses of significant main effects. In order to evaluate changes in the ear advantage compared to the no-noise condition, LI scores were calculated. Due to unbalanced design, LI scores for the noise conditions were only calculated across the intensity spectrum. *t*-tests for dependent samples were performed between the LI in the no-noise condition, the LI in the BNC and the LI for the BNT condition.

An REA was found for all conditions, however, the presence of background noise led to a reduction of the REA, more so in the BNT condition, particularly due to decreased right ear correct reports, replicating findings of Report I. Second, sound intensity was shown to play an important modulator role for the general effect of background noise since the REA decreased with increasing background noise intensity. Background noise intensity more affected the right ear stimuli, particularly at the highest intensity levels. Furthermore, overall performance was shown to decrease with increasing intensity level particularly in the BNT condition. The mean scores for left ear and right ear correct reports (%) for the BNC and the BNT condition at the four intensity levels are shown in Figure 5. The effects were discussed in terms of alertness and attentional mechanisms. It was further suggested that limitations of processing capacity of the hemispheres in loud noise may have also led to the present intensity effects at high intensity levels.

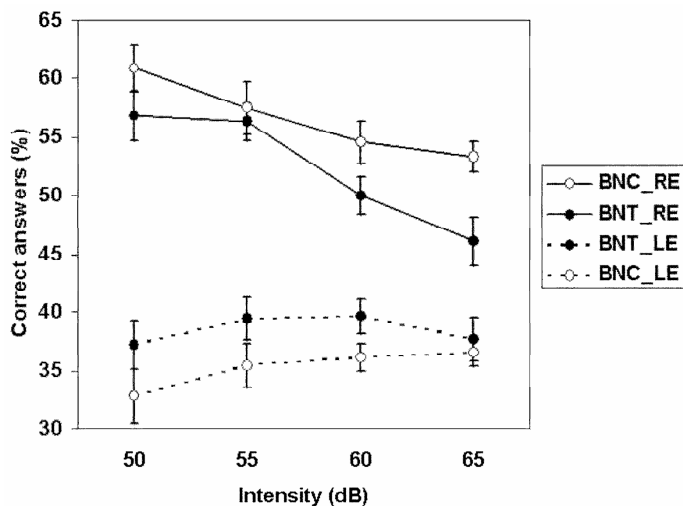


Figure 5: Mean scores for left ear and right ear correct reports (%) for the two different background noise conditions at four intensity levels. Vertical bars indicate standard errors of the mean.

### 6.3. Report III

To identify brain areas which may underlie the behavioral effects of different background noises on functional brain asymmetry in the DL task, hemodynamic brain responses using fMRI were recorded while subjects performed the DL task in two different noisy backgrounds ('babble' and traffic noise). A total of six types of trials were programmed in experiment III: CV-syllable pairs with either no background noise (CV condition), with babble background noise (BNC\_CV condition), or with traffic background noise (BNT\_CV condition). In addition, the paradigm contained trials where either babble noise (BNC only condition) or traffic noise (BNT only condition) was presented without the CV-syllable pairs. The background noise was presented at 60 dB throughout the experiment. Additional null events (SILENCE condition) were included according to the rules of stochastic design (Friston et al., 1999). The order of presentation of the trials was randomized and arranged as a single-session, event-related paradigm. We used a sparse sample acquisition paradigm with a silent gap between MR volume acquisitions, where the auditory stimuli were presented.

A 3.0-T (Tesla) GE Signa MRI system was used to acquire a total of 214 volumes (EPI sequence with 25 slices, slice thickness = 5 mm, inter-slice gap = 0.5 mm, TR 7 s, TE 30 ms, 90° flip angle, FOV 220 x 220 mm<sup>2</sup>, 64 x 64 matrix). The orientation of the axial slices was parallel to the AC-PC line. Acquisition time was 1.5 s leading to a silent gap of 5.5 s, in which the stimuli were presented and the verbal response was recorded. The first three volume images of each individual were discarded to reach maximum signal equilibrium.

For the data pre-processing and statistical analysis the Statistical Parametric Mapping analysis software package (SPM 5, Wellcome Department of Cognitive Neurology, London) implemented in MATLAB6.5.1 (Mathworks Inc., Natick, MA, USA) was used, which is based on the general linear model (GLM) approach. The data were realigned and unwarped. A normalization to a symmetrical EPI template based on the MNI reference brain was performed. The normalized images were resampled to a cubic voxel size of 2 mm. Spatial smoothing was executed with a Gaussian kernel of 8 mm FWHM. The fMRI data for each participant were first analyzed with separate fixed-effects statistical models, using the hemodynamic response function (hrf) as basis function and using temporal filtering (cut-off period of the high-pass filter was set to 128 s to remove low-frequency drifts, AR(1) to correct for serial correlations). Areas with statistically significant changes in signal intensity were determined using the *t*-statistic on a voxel basis. To determine activation patterns when only CV-syllables are presented in silence, we calculated the contrast [CV > SILENCE].

Behavioral performance to the CV-syllables in noise is driven by both brain mechanisms processing the noise and brain mechanisms processing the CV-syllables. Therefore, the contrasts [BNC > SILENCE], and [BNT > SILENCE] were calculated, revealing brain activation for only noise, i.e. ‘babble’ and traffic processing in silence, respectively. Furthermore, two difference contrasts were calculated, to determine activation only produced by the CV-syllables. Thus, we subtracted the respective noise condition from the condition in which CVs and noise were presented simultaneously, [(BNC\_CV) > (BNC)] and [(BNT\_CV) > (BNT)]. By calculating those contrasts, it is possible to study the single effects of noise- and CV-processing that may interactively drive behavioral performance. For the group analyses, these individual contrasts were then subjected to one-sample *t*-tests. The results were explored at an FWE (family-wise error) corrected statistical threshold of  $p < 0.01$  and only clusters with at least 10 significant voxels were considered. Because we were especially interested in activation patterns in areas of the auditory cortex, we further investigated the average signal change for all voxels in a region of interest (ROI) analysis. Therefore, we selected a ROI covering the whole STG. In order to perform further ROI analyses of specific subregions in the auditory cortex, we selected two smaller ROIs covering the HG, and the posterior part of the STG (i.e. PT) (cfr. Specht & Reul, 2003). Moreover, we performed a ROI analysis of the STG/SMG area. The definitions of the ROIs were based on the Masks for Region of Interest Analysis (MARINA) software program (Walter et al., 2003). From each region, the average signal change was extracted and statistical comparisons (paired *t*-tests) between the hemispheres and between the conditions were performed on a group-level, in which  $p < 0.05$  indicated a significant difference.

Analysis of behavioral data was similar to the analysis in Report I and yielded similar results (Figure 6), thus confirming the proposed alertness-attentional model.

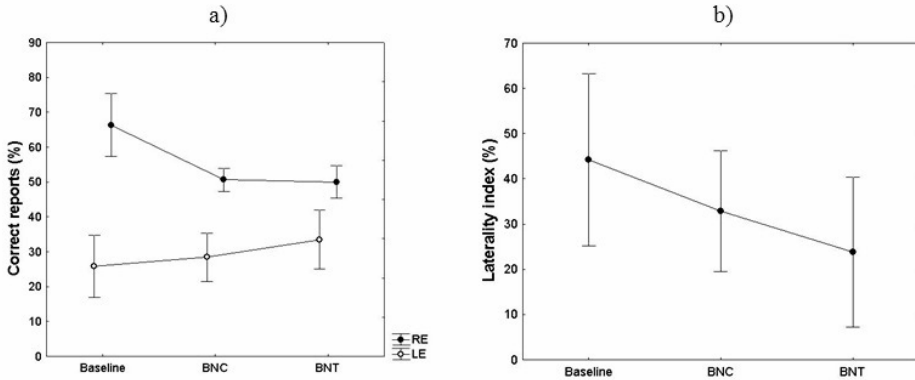


Figure 6: (a) Mean left ear and right ear correct reports (%) and (b) mean laterality index scores for the three different background noise conditions. Vertical bars indicate 0.95 confidence intervals.

Statistical analyses of the imaging data revealed left-lateralized activations in a distributed network including mainly temporal, and motor, and to a lesser extent frontal and parietal brain areas in the CV condition compared to the silence condition. Even though additional ROI analyses between the hemispheres revealed no significant findings, they show a tendency of a left-lateralization which may point to the proposed ventral and dorsal processing streams in the human auditory system (e.g. Binder et al., 2000; Hickok & Poeppel, 2000; Specht & Reul, 2003). CV processing together with babble noise revealed almost identical activation outside the temporal areas compared to the CV condition, while only small activation remained in the left peri-Sylvian region (BA 22/48), which was significant different from activation in this region in the CV condition as revealed by the additional ROI analyses. Small activation was also seen in the left temporo-parietal junction (STG/supramarginal gyrus (SMG)), which was smaller, but however not significantly different from STG/SMG activation in the CV condition. In the right hemisphere, activation was found in the STG/STS area (BA 21/22). CV processing in traffic noise yielded a similar activation network as seen in the CV condition. Figure 7 shows renderings of significant activations for the calculated contrasts. The results are attributed to pre-activation mechanisms initiated by the background noise affecting the processing of subsequent CV-stimuli.

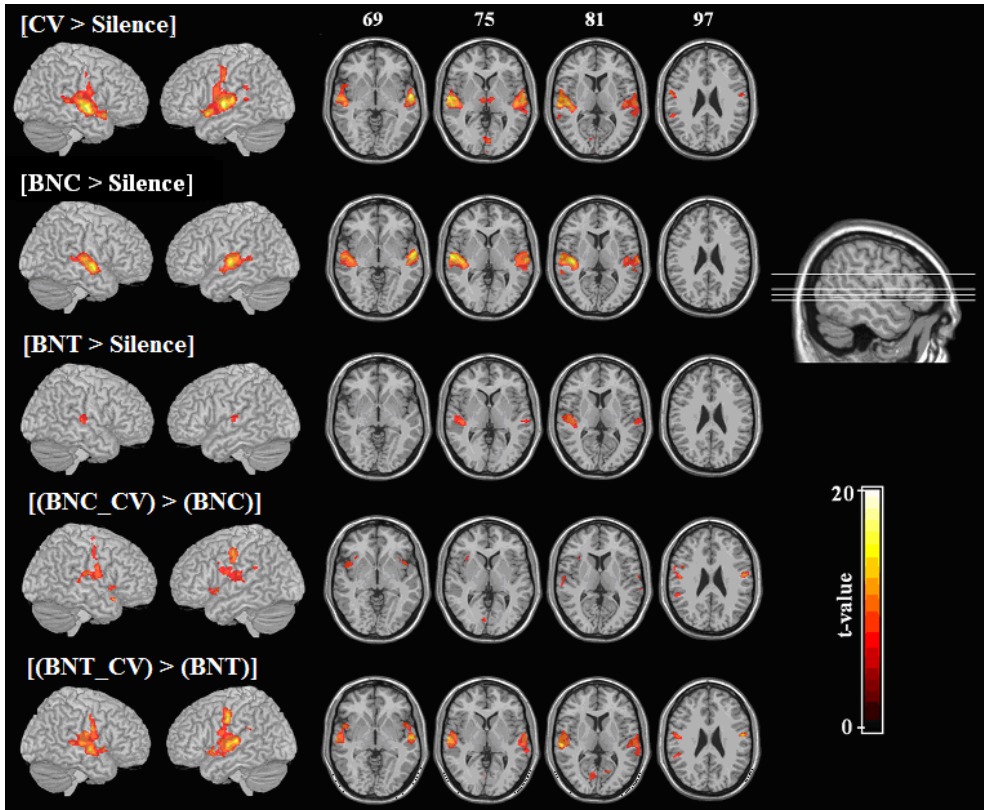


Figure 7: Renderings of significant activations ( $p < 0.01$ ; FWE corrected) on a 3D anatomy template are shown for [CV > Silence], [BNC > Silence], [BNT > Silence], [(BNC\_CV) > (BNC)], and [(BNT\_CV) > (BNT)] contrasts. Representative slices with differential activation in anterior and posterior STG regions ( $z = -3$ ,  $z = 9$ ,  $z = 25$ ) are additionally seen for the five contrasts.

## 7. Discussion

### 7.1. General discussion

#### *The effects of background noise on behavioral asymmetry of speech perception*

The first question of the present thesis concerned the effects of two different types of background noises on the behavioral asymmetry of speech perception. In all three Reports babble and traffic noise was used as ecologically valid background noise, and performance in the Bergen DL task was measured to test the asymmetry of speech perception. In all three Reports a significant REA was found for all conditions, replicating earlier findings (e.g. Hiscock & MacKay, 1985; Young & Ellis, 1980). However, in those conditions in which background noise was presented simultaneously, the REA was modulated. Modulation of REA in DL due to noise was also observed in earlier studies (e.g. Godfrey, 1974; Koroleva & Shurgaya, 1997; Weiss & House, 1973; see also Shtyrov et al., 1998 for further references; but see also Cullen et al., 1974). In the present Reports, babble and traffic background noise led to a decrease of the REA, as it was indicated by the smaller REA in the babble and traffic background noise conditions compared to the baseline (i.e. CV, no-noise) condition.

When the effect of background noise on the right and left ear stimuli were analyzed separately in Report I, we observed a reduced performance only for the right ear scores. An opposite effect was observed for the left ear scores. A similar pattern of results was found in Report II and III, which argues for the strength and robustness of the effect. Even when the subjects were placed in the MRI scanner, a quite different and for some participants even a stress-situation compared to the behavioral-only testing in the acoustically shielded room, the behavioral results were similar. The differential effect of the background noise on the left and right ear is in line with effects observed by Koroleva and Shurgaya (1997) who demonstrated a stronger decrease in the number of correct reports from the right ear compared to the left ear in noise. The present results are also similar to those reported in a study by Shtyrov et al. (1998; 1999; but see also Kozou et al., 2005), who measured MMNm to a speech-signal discrimination task in noise. Although Shtyrov and colleagues used a different approach to measure lateralization of hemisphere function, and although changes in MMNm may not be comparable to changes in behavior in DL, one may still draw some parallels. The authors also observed that noise influence the left and right hemisphere differently. More precisely, they observed a decrease of the MMNm elicited by deviant syllables in the left hemisphere, and an

increase of the MMNm in the right hemisphere in the noise conditions. They suggest a redistribution of the lateralization of the speech-sound discrimination function between the hemispheres in background noise, i.e. not only the dominant hemisphere but both hemispheres are suggested to be involved in speech-sound discrimination in noise (Shtyrov et al., 1998). Correspondingly, neuroimaging studies by Muller-Gass et al. (2001) and by Hwang et al. (2006) may also be interpreted in a similar way since their data showed a more detrimental effect of noise in the left hemisphere. This may support the idea of a shift of activation from the left to the right hemisphere in a noisy listening situation. The reorganization of speech processing in workers exposed to long-term occupational noise (Brattico et al., 2005; Kujala et al., 2004) provides further evidence that background noise alters lateralized speech perception processes.

The implementation of two background noises in the present thesis, i.e. babble and traffic background noise, allows drawing comparisons regarding their different effects on the behavioral asymmetry of speech perception. This represents an enormous advantage compared to earlier studies using only one type of noise (e.g. Godfrey, 1974; Koroleva & Shurgaya, 1997). In all three Reports, a stronger decrease in REA was observed in the traffic noise condition compared to the babble noise condition. Moreover, the separate analysis of right and left ear stimuli revealed a reduced performance only for the right ear scores. This effect was stronger for the traffic background noise compared to the babble background noise. The difference in the degree of modulation of the REA between the two background noise conditions cannot be attributed to acoustic characteristics since comparing and analyzing the frequency spectra of the noises both visually and statistically for all frequency categories in 250 Hz steps revealed no significant differences. Hence, it can be assumed that the acoustic characteristics of the traffic and babble noise are approximately similar. Although not using a DL task, other studies revealed similar results with individuals being less affected by speech background noise compared to random (white) noise (e.g. Hygge, Rönnerberg, Larsby, & Arlinger, 1992). This effect was proposed to be due to the temporal pattern of speech (e.g. fluctuations, amplitude variations). However, the different effects of the babble and traffic background noise in the present thesis cannot be attributed to different temporal patterns since they were approximately the same for both traffic and babble background noise. The traffic background noise may have been perceived as more disturbing than the babble background noise, and may have thus been perceived as more interfering than the babble background noise. The perceptual apparatus may have better adapted to situations where it is necessary to filter out irrelevant background speech than irrelevant other sounds.

Alternatively, the detrimental effects of noise that are observed in all three Reports may have been due to an interplay of alertness and attentional mechanisms, which we have proposed in a two-factor alertness-attentional model.

*The two-factor alertness-attentional model*

The effects of background noise on the REA in the DL task with CV-syllables can be explained as that performing the DL task in noisy background conditions may require additional cognitive capacity and control, accounted for by two factors: a general alertness factor and an attentional pre-activation factor.

Building on the suggestion that the right hemisphere is important for alertness (Sturm et al., 1999; Sturm et al., 2004), we suggest that an increase in the left ear correct reports in both the babble and traffic background noise conditions compared to the baseline, i.e. no-noise CV condition may be due to an increase in right hemisphere alertness in these conditions. This may in turn cancel out an eventual detrimental effect of noise for the left ear stimuli. An increase of activation in the right hemisphere may therefore cause a conflict with the dominance of the left hemisphere for processing CV-syllables. This conflict may result in a reduction of the REA in the babble and in the traffic background noise condition as a kind of “balanced” processing of the stimuli. Acoustic interference may play a role under comparable stimulus conditions via an additive central processing mechanism that combines left and right ear stimulus information, as suggested by Cullen et al. (1974). The smaller REA, which occurs when traffic background noise was presented simultaneously compared to babble background noise, points to a more detrimental effect of traffic than conversation background noise. That traffic background noise is generally considered as being stressful, evoking a negative emotional valence and adversely affecting people’s well being may have contributed to the more detrimental effect of traffic compared to babble background noise (Davidson, 1995; Ouis, 2001; Vera, Vila, & Godoy, 1992). Therefore, traffic background noise may have elicited a higher level of right hemisphere alertness compared to babble background noise, resulting in a more advantageous effect on the left ear stimuli. Returning to the proposed “balance” between the hemispheres, the greater alertness of the right hemisphere in the traffic condition may also have caused more conflict with CV-syllable processing of the left hemisphere, resulting in an even more pronounced reduction of the REA in the traffic compared to the babble background noise condition.



With regard to the differential effects of babble and traffic noise, an attentional pre-activation factor has been suggested. In addition to a general alertness factor, attentional mechanisms following the model proposed by Kinsbourne (1970; see also Hiscock & Kinsbourne, 1980) may have contributed to the smaller REA in the traffic compared to the babble background noise condition. As previously proposed, noise may have elicited right hemisphere alertness accompanied by increased processing of the left ear stimuli. Hence, a direct decreasing effect of background noise on the left ear stimuli may have been cancelled out, while a decreasing effect of background noise on the right ear stimuli may have still been present. Additional attentional mechanisms may then, in the case of babble background noise, have primed the left hemisphere, and thus counteracted the direct degrading effect of noise on the right ear stimuli. This process may have prevented right ear performance from decreasing as would be expected as a consequence of interference or degradation. This would result in a net effect of a smaller reduction in the REA in the babble compared to the traffic background noise condition. In the case of non-verbal traffic background noise, pre-activation of the right hemisphere, i.e. directed attention to the left ear, may lead to an even greater benefit for the right hemisphere, and at the same time to a more pronounced reduction of the right ear stimuli since a decrease due to interference or degradation would not be counteracted as it was in the babble background noise condition. Hence, non-verbal traffic background noise leads to a stronger attenuation of the REA compared to the babble background noise.

#### *The effects of intensity*

The second research question concerned the effects of different intensity levels of the two background noises on DL performance. Therefore, we varied the intensity of the babble and traffic background noise between 50 and 65 dB in steps of 5 dB in Report II. As a result of increasing background noise intensity, a decrease in the REA was observed, suggesting that intensity plays an important modulator role for the general effect of background noise. Moreover, background noise effects were stronger for the right ear, and for the traffic noise condition – similar to the findings in Report I – that was particularly true for the 60 and 65 dB conditions. The finding of a reduction only for the right ear stimulus supports the proposed alertness mechanism. Alertness which benefits the right hemisphere (cfr. Sturm et al., 1999; Sturm et al., 2004) and thus interferes with the left hemisphere, may be increased with a corresponding increase in noise intensity. The presence of a loud and strong background noise (i.e. 60 and 65 dB) may not only alert the right hemisphere to a maximum, but also require

resources of the left hemisphere. This in turn may limit the processing capacity of the left hemisphere to perceive and identify the CV-syllables, leading to a decrease in right ear correct reports with higher noise intensities. The smaller REA in the traffic compared to the babble background noise conditions points to a more detrimental effect of traffic than babble background noise, as it was already revealed in Report I. The detrimental effect of traffic background noise was due to reduced right ear correct reports, and points to attentional factors proposed in the two-factor alertness-attentional model. In addition, the effect of traffic background noise was especially striking at the two highest intensity levels (i.e. 60 and 65 dB), probably due to strong feelings of annoyance/displeasure in a traffic situation that may be dependent on intensity level (Berglund, Preis, & Rankin, 1990) and that may not occur until the traffic noise is of high intensity (>60 dB). Babble background noise may only arouse the same amount of annoyance when it is presented in an even higher intensity level compared to the traffic background noise. The results in Report II signify the importance to consider both intensity level of the background noise and noise type in the study of auditory laterality.

#### *Effects of background noise on neuronal activation in a DL task*

The third research question concerned neuronal processes that may underlie the effects of traffic and babble background noise on asymmetrical speech perception in a DL task. Therefore, hemodynamic brain responses using fMRI were recorded while subjects performed the DL task with CV-syllables in traffic and babble background noise in Report III. The behavioral data revealed similar results to those in Report I with a reduction of REA due to increased left and decreased right ear performance, especially in the traffic noise condition. Again, the two-factor attentional-alertness model was proposed.

When looking at the effects of noise on brain activation, especially changes in speech-processing areas were observed, as it was hypothesized. The DL task presented without background noise evoked left-lateralized activation in a distributed network, similar to activation patterns seen in previous studies (Jäncke, Buchanan, Lutz, & Shah, 2001; Jäncke, Specht, Shah, & Hugdahl, 2003; van den Noort, Specht, Rimol, Ersland, & Hugdahl, 2008), and matching the behavioral performance in the CV condition. The activation pattern in the temporal lobe, comprising areas in the primary and secondary auditory cortices, extending to the STS and to the superior temporal pole together with activation in left SMG may point to

the ventral and dorsal processing stream in the human auditory system (Binder et al., 2000; Hickok & Poeppel, 2000, 2007; Specht & Reul, 2003; Wise et al., 2001).

When CV-syllables were presented together with babble background noise, only small remaining activation was found in the left peri-Sylvian region. The changes in activation patterns may be explained by pre-activation mechanisms: The presentation of verbal background noise (i.e. babble) before the presentation of the CV-syllable may have already pre-activated left and right auditory areas. Pre-activation may thus affect the processing of subsequent auditory stimuli, i.e. the CV-syllables. In consequence, the presentation of additional subsequent verbal CV-syllables resulted in no further activation in the already pre-activated speech relevant areas. This suggestion is substantiated by the significant activation pattern in these areas in the babble only condition. Pre-activation may thus mediate further processing of subsequent CV-syllables, as reflected in modulation of left and right ear performance. Activation was also found in the left temporo-parietal junction (STG/SMG), an area that was not pre-activated by the babble. This may indicate, that in order to process the CV-syllables in babble noise, this area has to be additionally activated compared to the babble only condition.

In the right hemisphere, however, activation was observed in the STG/STS region, a region that was already pre-activated by babble. This finding may suggest enhanced processing in these areas when CV-syllables were processed together with babble noise, maybe due to additional effort that has to be engaged.

When CV-syllables were presented together with traffic background noise, activations were found to be similar to activations in the CV condition. Pre-activation mechanisms may not apply when non-verbal traffic background noise was presented before the CV-syllables, since traffic noise did not contain phonological features. Thus, neuronal areas involved in processing of verbal stimuli were not, or only slightly, activated until the presentation of the CV-syllables. Activation in left STG/SMG may together with the observed activation in the same region in CV processing in babble noise, suggest that this area may be activated whenever CV-syllables are present. The left temporo-parietal junction was previously suggested to be a part of a sensory-motor integration circuit for the vocal tract (Hickok & Poeppel, 2007; Pa & Hickok, 2008), a suggestion that agrees with the present results; Whenever CV-syllables are present and a verbal answer of the subject is asked for, the temporo-parietal junction is activated, mapping the sensory or phonological representations

onto articulatory motor representations, and thus tuning the motor system to produce a verbal gesture.

To conclude, pre-activation mechanisms and CV-processing mechanisms may both interactively, but to a different degree, account for the BOLD activation to CV-syllables in noise. In babble, pre-activation to the verbal noise per se may have preceded CV-syllable processing, and thus may have by itself constitute the observed brain activation that underlie CV-processing in babble noise. However, in traffic, a different neurocircuitry was observed, indicating that no pre-activation preceded CV-syllable processing and thus, mainly processing of the CV-syllables may have led to brain activation in traffic noise. Looking at behavioral performance in terms of the laterality index it may be suggested that pre-activation processes in babble background noise may have prevented the REA to decrease to such a degree as it was observed for the traffic background noise, where no pre-activation was indicated. However, pre-activation and CV-processing mechanisms may not sufficiently explain the effects of noise on behavior. Thus, additional factors may be involved in CV processing in babble and in traffic noise. Alertness and attentional mechanisms have been originally suggested to account for the behavioral results, but there was no specific activation pattern that may have indicated an one-to-one mapping of those mechanisms. Regarding alertness, we proposed, that whenever the subjects hear either traffic or babble noise, they may exhibit right-hemisphere alertness (cfr. Sturm et al., 1999; Sturm et al., 2004). Thus, alertness may be present in all noise conditions, with or without the subsequent presentation of CV-syllables. Hence, mapping alertness may be difficult, since it may automatically be deducted in the contrasts.

Since the behavioral results are not obviously reflected in the observed BOLD signals, it may be hypothesized that performance may rather be reflected in interactions or integration within distributed neural systems in terms of effective connectivity. Variations in performance may be driven by variations in this coupling among neuronal activation in different regions. The calculation of a DCM (dynamic causal modeling; Friston, Harrison, & Penny, 2003) analysis may help to answer this question, however, the unbalanced design in the present thesis may complicate such an approach.

Modulations of the level of neuronal activation may not lead to corresponding modulations in the level of the BOLD response, as it is postulated by the Linear Transform Model (e.g. Burke & Bührle, 2006; Heeger & Ress, 2002; Marcar, Straessle, Girard,

Loenneker, & Martin, 2004), thus, the BOLD response may not necessarily reflect the level of activation within a neuronal activation network that may drive the performance at the behavioral level. In addition, modulation of the level of neuronal activation may also not necessarily go along with modulation in the same direction of the level of behavioral performance. Hence, the attempt to find a one-to-one mapping in BOLD response pattern tapping the behavioral performance may not be feasible. Moreover, BOLD-fMRI may not be sensitive enough to detect additional processes that may have led to the behavioral results, as for example alertness and attentional mechanisms.

## 7.2. Implications and future work

The results of the three Reports support earlier suggestions that the REA to phonological stimuli is prone to certain experimental conditions and interindividual differences. Beside background noise, it has been shown that for example stimulus features (Hugdahl, Westerhausen, Alho, Medvedev, & Hämäläinen, 2008; Sandmann et al., 2007), attentional instructions (Hugdahl et al., 2000; Jäncke et al., 2003; O'Leary et al., 1996), handedness (Dos Santos Sequeira et al., 2006), brain lesions (Hugdahl & Wester, 1992), and psychological disorders such as dyslexia and schizophrenia (Cohen, Hynd, & Hugdahl, 1992; Hugdahl, Helland, Færevåg, Lyssand, & Asbjørnsen, 1995; Hugdahl, Rund et al., 2003; Løberg et al., 1999) also influence the REA, indicating that left hemispheric speech perception predominance is vulnerable to a variety of perceptual and cognitive factors. Thus, when investigating lateralization of speech perception, all of those factors have to be taken into account. Since it was shown in Report II that intensity level mediate the effects of background noise on DL performance, varying the intensity levels should also be taken into account in future studies, looking for possible intensity by background noise interactions. At the same time, the present results raise a general question whether speech lateralization as it is commonly tested, i.e. in laboratory silence, actually reflect auditory lateralization as it occurs in everyday listening situations. External validity may be increased when the experimental test situation is made as close to the everyday situation as possible, for example by additionally implementing background noise.

The BOLD response pattern in the CV condition may argue for the dual stream model of speech perception postulated by Hickok and Poeppel (2000, 2007). After spectro-temporal analysis and phonological level processing in dorsal STG and middle to posterior STS,

respectively, the authors suggest two pathways, a ventral processing stream including posterior parts of the middle temporal gyrus (MTG) and extending to more anterior parts of the MTG, and a dorsal processing stream, including area Spt (Sylvian parietal temporal area) and extending to frontal parts (posterior part of the inferior frontal gyrus, premotor cortex, and anterior insula), where further processing, i.e. processing for comprehension and mapping onto articulatory motor representations, is thought to take place in parallel (Hickok & Poeppel, 2000, 2007). CV processing in the present thesis resulted in activation especially in the peri-Sylvian part of the STG, comprising areas in the primary and secondary cortices, extending to the STS and to more anterior parts that may correspond to a ventral processing stream, while activation in the left SMG may point to a dorsal processing stream. Further research needs to be done to substantiate this model of the cortical organization of speech processing, and more specifically to identify the architecture and the exact processes that underlie both processing streams and to specify the details of the organization within both processing streams in order to more exactly interpret and integrate the present findings.

In contrast to most previous studies using white noise, two day-to-day background noises, i.e. conversational babble and traffic noise were used in the present Reports. Using realistic noises increases the ecological validity of the test. Future studies may include other realistic noises, for example noises that may often be found in offices such as telephone ringing, construction work noise, air conditioning, etc. The present Reports revealed traffic noise in particular to affect speech lateralization, however, traffic noise is generally considered as stressful, and adversely affecting people's well being (Ouis, 2001), thus it would also be of interest for future investigations to study the effects on the REA using background noises that have not been considered as stressful, for example bird singing or crashing seas.

Although the babble and the traffic background noise in the present Reports were used as examples of common environmental background noises, the absence of a spatial component, as for example the Doppler-like effect when traffic is moving to and away, is a limitation to the everyday realism of the stimuli, in particular with respect to sound localization. This may affect generalization of the findings to other situations. It may be advisable to take into account a spatial component when creating the background noises in future studies, however, a spatial component may influence attention and thus may play a confounding variable in the investigation of the effects of noise per se on the REA.

Another factor that should be controlled for in future studies is the number of speakers that make up the babble noise. Since it was shown that the number of speakers influences the degree of disruption on performance (Jones & Macken, 1995; Simpson & Cooke, 2005), this factor may also play an important role when studying the processing of phonological stimuli, since an increase in intelligibility, i.e. an improvement in the recognizability of some important acoustic attributes, such as phonetic features, may lead to a decrease in performance due to competition in processing resources.

Furthermore, possible negative emotional valence possibly evoked by the traffic noise but not by the babble noise may have contributed to the differential interference (Davidson, 1995; Vera, Vila, & Godoy, 1992).

In order to study the effects of different noises, it may furthermore be interesting to use noises that are not lateralized in the first place. Thus, following the idea of soundmorph sounds by Specht and colleagues (Specht, Rimol, Reul, & Hugdahl, 2005), traffic noise and babble noise may be morphed together yielding one noise that may not be processed asymmetrically in the first place.

BOLD-fMRI that was used as the single imaging method in the present thesis may not be sensitive enough to exactly map the processes that stand behind the hypothesized mental operations which are necessary to process CV-syllables together with traffic and babble background noise. By contrast, EEG and MEG methods are more sensitive to transient neurophysiological processes, allowing to measure different aspects of speech perception in noise. Thus, a promising approach would be to perform combined measurements, such as EEG and fMRI during DL in noise. Eichele and colleagues (2005) for example integrated fMRI with ERPs to achieve a better understanding of the temporal order of different brain activation patterns (Eichele et al., 2005). This approach may provide a more conclusive understanding of the underlying mechanisms (e.g. pre-activation, alertness, attention) in the present thesis. Those mechanisms may have been initiated at different latencies in the babble and traffic noise conditions and hence may have driven the observed differences in modulation of the dichotic REA.

Additionally, the present thesis points to applied implications by providing new knowledge for design of, for instance, workplace environments, for example in aviation, where pilots have continuously to deal with irrelevant background speech that has to be

ignored, but which at the same time is important in helping to maintain “situation awareness” (Beaman, 2005; Mogford, 1997; Pritchett & Hansman, 1996).

To conclude, the present thesis, although including some limitations, reveals the effects of noise on asymmetrical speech perception and thus gives some insights in how the brain processes speech in a day-to-day listening situation. The findings of the present Reports pose new research questions that are essential to be examined in the future in order to get a more complete understanding of perception and cognition.



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## ERRATA

### 1. Page 33, Figure 3:

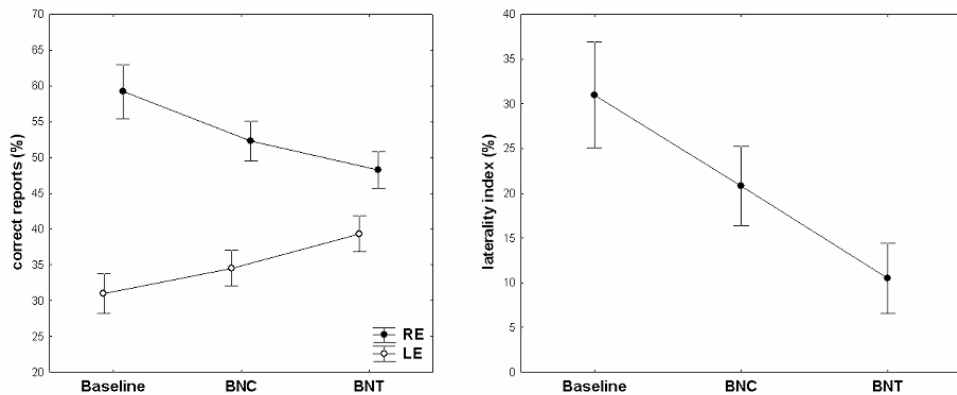
Change Figure legend to „A statistical map of fMRI data displayed on a background anatomical MR image. Areas of statistically significant activation are shown in color. Hot colorscale indicates t-statistics.”

### 2. Page 39, line 15:

Change “...while higher-order processing was found to be enhanced...” to “...while higher-order processing was found to be reduced...”

### 3. Page 48, Figure 4:

Change Figure to:



### 4. Page 53, Figure 7:

Change Figure legend to: “Renderings of significant activations ( $p < 0.01$ ; FWE corrected) on a 3D anatomy template are shown for [CV > Silence], [BNC > Silence], [BNT > Silence], [(BNC\_CV) > (BNC)], and [(BNT\_CV) > (BNT)] contrasts. Representative slices with differential activation in anterior and posterior STG regions ( $z = 69$ ,  $z = 75$ ,  $z = 81$ ,  $z = 97$ ) are additionally seen for the five contrasts.”

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**5. Page 67:**

Change “Bryden, M. P. (1988). Correlates of the dichotic right-ear effect. *Cortex*, 24, 313-319.” to “Bryden, M. P. (1988). An overview of the dichotic listening procedure and its relation to cerebral organization. In K. Hugdahl (Ed.), *Handbook of Dichotic Listening: Theory, methods, and research* (pp. 1-44). Chichester, UK: Wiley & Sons.”





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- Braathen, E.T., Dr. psychol. Prediction of excellence and discontinuation in different types of sport: The significance of motivation and EMG.
- Johannessen, B.F., Dr. philos. Det flytende kjønnet. Om lederskap, politikk og identitet.
- 1995** Sam, D.L., Dr. psychol. Acculturation of young immigrants in Norway: A psychological and socio-cultural adaptation.
- Bjaalid, I.-K., Dr. philos. Component processes in word recognition.
- Martinsen, Ø., Dr. philos. Cognitive style and insight.
- Nordby, H., Dr. philos. Processing of auditory deviant events: Mismatch negativity of event-related brain potentials.
- Raaheim, A., Dr. philos. Health perception and health behaviour, theoretical considerations, empirical studies, and practical implications.
- Seltzer, W.J., Dr. philos. Studies of Psychocultural Approach to Families in Therapy.
- Brun, W., Dr. philos. Subjective conceptions of uncertainty and risk.
- Aas, H.N., Dr. psychol. Alcohol expectancies and socialization: Adolescents learning to drink.
- Bjørkly, S., Dr. psychol. Diagnosis and prediction of intra-institutional aggressive behaviour in psychotic patients
- 1996** Anderssen, N., Dr. psychol. Physical activity of young people in a health perspective: Stability, change and social influences.
- Sandal, Gro Mjeldheim, Dr. psychol. Coping in extreme environments: The role of personality.
- Strumse, Einar, Dr. philos. The psychology of aesthetics: explaining visual preferences for agrarian landscapes in Western Norway.
- Hestad, Knut, Dr. philos. Neuropsychological deficits in HIV-1 infection.
- Lugoe, L. Wycliffe, Dr. philos. Prediction of Tanzanian students' HIV risk and preventive behaviours.
- Sandvik, B. Gunnhild, Dr. philos. Fra distriktsjordmor til institusjonsjordmor. Fremveksten av en profesjon og en profesjonsutdanning.

	Lie, Gro Therese, Dr. psychol.	The disease that dares not speak its name: Studies on factors of importance for coping with HIV/AIDS in Northern Tanzania.
	Øygaard, Lisbet, Dr. philos.	Health behaviors among young adults. A psychological and sociological approach.
	Stormark, Kjell Morten, Dr. psychol.	Emotional modulation of selective attention: Experimental and clinical evidence.
	Einarsen, Ståle, Dr. psychol.	Bullying and harassment at work: epidemiological and psychosocial aspects.
<b>1997</b>	Knivsberg, Ann-Mari, Dr. philos.	Behavioural abnormalities and childhood psychopathology: Urinary peptide patterns as a potential tool in diagnosis and remediation.
	Eide, Arne H., Dr. philos.	Adolescent drug use in Zimbabwe. Cultural orientation in a global-local perspective and use of psychoactive substances among secondary school students.
	Sørensen, Marit, Dr. philos.	The psychology of initiating and maintaining exercise and diet behaviour.
	Skjæveland, Oddvar, Dr. psychol.	Relationships between spatial-physical neighborhood attributes and social relations among neighbors.
	Zewdie, Teka, Dr. philos.	Mother-child relational patterns in Ethiopia. Issues of developmental theories and intervention programs.
	Wilhelmsen, Britt Unni, Dr. philos.	Development and evaluation of two educational programmes designed to prevent alcohol use among adolescents.
	Manger, Terje, Dr. philos.	Gender differences in mathematical achievement among Norwegian elementary school students.
<b>1998</b>		
V	Lindstrøm, Torill Christine, Dr. philos.	«Good Grief»: Adapting to Bereavement.
	Skogstad, Anders, Dr. philos.	Effects of leadership behaviour on job satisfaction, health and efficiency.
	Haldorsen, Ellen M. Håland, Dr. psychol.	Return to work in low back pain patients.
	Besemer, Susan P., Dr. philos.	Creative Product Analysis: The Search for a Valid Model for Understanding Creativity in Products.
H	Winje, Dagfinn, Dr. psychol.	Psychological adjustment after severe trauma. A longitudinal study of adults' and children's posttraumatic reactions and coping after the bus accident in Måbødalen, Norway 1988.
	Vosburg, Suzanne K., Dr. philos.	The effects of mood on creative problem solving.
	Eriksen, Hege R., Dr. philos.	Stress and coping: Does it really matter for subjective health complaints?

	Jakobsen, Reidar, Dr. psychol.	Empiriske studier av kunnskap og holdninger om hiv/aids og den normative seksuelle utvikling i ungdomsårene.
<b>1999</b>		
V	Mikkelsen, Aslaug, Dr. philos.	Effects of learning opportunities and learning climate on occupational health.
	Samdal, Oddrun, Dr. philos.	The school environment as a risk or resource for students' health-related behaviours and subjective well-being.
	Friestad, Christine, Dr. philos.	Social psychological approaches to smoking.
	Ekeland, Tor-Johan, Dr. philos.	Meining som medisin. Ein analyse av placebofenomenet og implikasjoner for terapi og terapeutiske teoriar.
H	Saban, Sara, Dr. psychol.	Brain Asymmetry and Attention: Classical Conditioning Experiments.
	Carlsten, Carl Thomas, Dr. philos.	God lesing – God læring. En aksjonsrettet studie av undervisning i fagtekstlesing.
	Dundas, Ingrid, Dr. psychol.	Functional and dysfunctional closeness. Family interaction and children's adjustment.
	Engen, Liv, Dr. philos.	Kartlegging av leseferdighet på småskoletrinnet og vurdering av faktorer som kan være av betydning for optimal leseutvikling.
<b>2000</b>		
V	Hovland, Ole Johan, Dr. philos.	Transforming a self-preserving "alarm" reaction into a self-defeating emotional response: Toward an integrative approach to anxiety as a human phenomenon.
	Lillejord, Sølvi, Dr. philos.	Handlingsrasjonalitet og spesialundervisning. En analyse av aktørperspektiver.
	Sandell, Ove, Dr. philos.	Den varme kunnskapen.
	Oftedal, Marit Petersen, Dr. philos.	Diagnostisering av ordavkodingsvansker: En prosessanalytisk tilnæringsmåte.
H	Sandbak, Tone, Dr. psychol.	Alcohol consumption and preference in the rat: The significance of individual differences and relationships to stress pathology.
	Eid, Jarle, Dr. psychol.	Early predictors of PTSD symptom reporting; The significance of contextual and individual factors.
<b>2001</b>		
V	Skinstad, Anne Helene, Dr. philos.	Substance dependence and borderline personality disorders.
	Binder, Per-Einar, Dr. psychol.	Individet og den meningsbærende andre. En teoretisk undersøkelse av de mellommenneskelige forutsetningene for psykisk liv og utvikling med utgangspunkt i Donald Winnicotts teori.

	Roald, Ingvild K., Dr. philos.	Building of concepts. A study of Physics concepts of Norwegian deaf students.
H	Fekadu, Zelalem W., Dr. philos.	Predicting contraceptive use and intention among a sample of adolescent girls. An application of the theory of planned behaviour in Ethiopian context.
	Melesse, Fantu, Dr. philos.	The more intelligent and sensitive child (MISC) mediational intervention in an Ethiopian context: An evaluation study.
	Råheim, Målfrid, Dr. philos.	Kvinneres kroppserfaring og livssammenheng. En fenomenologisk – hermeneutisk studie av friske kvinner og kvinner med kroniske muskelsmerter.
	Engelsen, Birthe Kari, Dr. psychol.	Measurement of the eating problem construct.
	Lau, Bjørn, Dr. philos.	Weight and eating concerns in adolescence.
<b>2002</b>		
V	Ihlebak, Camilla, Dr. philos.	Epidemiological studies of subjective health complaints.
	Rosén, Gunnar O. R., Dr. philos.	The phantom limb experience. Models for understanding and treatment of pain with hypnosis.
	Høines, Marit Johnsen, Dr. philos.	Fleksible språkrøm. Matematikklæring som tekstutvikling.
	Anthun, Roald Andor, Dr. philos.	School psychology service quality. Consumer appraisal, quality dimensions, and collaborative improvement potential
	Pallesen, Ståle, Dr. psychol.	Insomnia in the elderly. Epidemiology, psychological characteristics and treatment.
	Midthassel, Unni Vere, Dr. philos.	Teacher involvement in school development activity. A study of teachers in Norwegian compulsory schools.
	Kallestad, Jan Helge, Dr. philos.	Teachers, schools and implementation of the Olweus Bullying Prevention Program.
H	Ofte, Sonja Helgesen, Dr. psychol.	Right-left discrimination in adults and children.
	Netland, Marit, Dr. psychol.	Exposure to political violence. The need to estimate our estimations.
	Diseth, Åge, Dr. psychol.	Approaches to learning: Validity and prediction of academic performance.
	Bjuland, Raymond, Dr. philos.	Problem solving in geometry. Reasoning processes of student teachers working in small groups: A dialogical approach.
<b>2003</b>		
V	Arefjord, Kjersti, Dr. psychol.	After the myocardial infarction – the wives' view. Short- and long-term adjustment in wives of myocardial infarction patients.

	Ingjaldsson, Jón Þorvaldur, Dr. psychol.	Unconscious Processes and Vagal Activity in Alcohol Dependency.
	Holden, Børge, Dr. philos.	Følger av atferdsanalytiske forklaringer for atferdsanalysens tilnærming til utforming av behandling.
	Holsen, Ingrid, Dr. philos.	Depressed mood from adolescence to 'emerging adulthood'. Course and longitudinal influences of body image and parent-adolescent relationship.
	Hammar, Åsa Karin, Dr. psychol.	Major depression and cognitive dysfunction- An experimental study of the cognitive effort hypothesis.
	Sprugevica, Ieva, Dr. philos.	The impact of enabling skills on early reading acquisition.
	Gabrielsen, Egil, Dr. philos.	Lese for livet. Lesekompetansen i den norske voksebefolkningen sett i lys av visjonen om en enhetsskole.
H	Hansen, Anita Lill, Dr. psychol.	The influence of heart rate variability in the regulation of attentional and memory processes.
	Dyregrov, Kari, Dr. philos.	The loss of child by suicide, SIDS, and accidents: Consequences, needs and provisions of help.
<b>2004</b>		
V	Torsheim, Torbjørn, Dr. psychol.	Student role strain and subjective health complaints: Individual, contextual, and longitudinal perspectives.
	Haugland, Bente Storm Mowatt Dr. psychol.	Parental alcohol abuse. Family functioning and child adjustment.
	Milde, Anne Marita, Dr. psychol.	Ulcerative colitis and the role of stress. Animal studies of psychobiological factors in relationship to experimentally induced colitis.
	Stornes, Tor, Dr. philos.	Socio-moral behaviour in sport. An investigation of perceptions of sportpersonship in handball related to important factors of socio-moral influence.
	Mæhle, Magne, Dr. philos.	Re-inventing the child in family therapy: An investigation of the relevance and applicability of theory and research in child development for family therapy involving children.
	Kobbeltvedt, Therese, Dr. psychol.	Risk and feelings: A field approach.
<b>2004</b>		
H	Thomsen, Tormod, Dr. psychol.	Localization of attention in the brain.
	Løberg, Else-Marie, Dr. psychol.	Functional laterality and attention modulation in schizophrenia: Effects of clinical variables.
	Kyrkjebø, Jane Mikkelsen, Dr. philos.	Learning to improve: Integrating continuous quality improvement learning into nursing education.
	Laumann, Karin, Dr. psychol.	Restorative and stress-reducing effects of natural environments: Experiential, behavioural and cardiovascular indices.

	Holgersen, Helge, PhD	Mellom oss - Essay i relasjonell psykoanalyse.
<b>2005</b>		
V	Hetland, Hilde, Dr. psychol.	Leading to the extraordinary? Antecedents and outcomes of transformational leadership.
	Iversen, Anette Christine, Dr. philos.	Social differences in health behaviour: the motivational role of perceived control and coping.
<b>2005</b>		
H	Mathisen, Gro Ellen, PhD	Climates for creativity and innovation: Definitions, measurement, predictors and consequences.
	Sævi, Tone, Dr. philos.	Seeing disability pedagogically – The lived experience of disability in the pedagogical encounter.
	Wiium, Nora, PhD	Intrapersonal factors, family and school norms: combined and interactive influence on adolescent smoking behaviour.
	Kanagaratnam, Pushpa, PhD	Subjective and objective correlates of Posttraumatic Stress in immigrants/refugees exposed to political violence.
	Larsen, Torill M. B. , PhD	Evaluating principals` and teachers` implementation of Second Step. A case study of four Norwegian primary schools.
	Bancila, Delia, PhD	Psychosocial stress and distress among Romanian adolescents and adults.
<b>2006</b>		
V	Hillestad, Torgeir Martin, Dr. philos.	Normalitet og avvik. Forutsetninger for et objektivt psykopatologisk avviksbegrep. En psykologisk, sosial, erkjennelsesteoretisk og teoriihistorisk framstilling.
	Nordanger, Dag Øystein, Dr. psychol.	Psychosocial discourses and responses to political violence in post-war Tigray, Ethiopia.
	Rimol, Lars Morten, PhD	Behavioral and fMRI studies of auditory laterality and speech sound processing.
	Krumsvik, Rune Johan, Dr. philos.	ICT in the school. ICT-initiated school development in lower secondary school.
	Norman, Elisabeth, Dr. psychol.	Gut feelings and unconscious thought: An exploration of fringe consciousness in implicit cognition.
	Israel, K Pravin, Dr. psychol.	Parent involvement in the mental health care of children and adolescents. Empirical studies from clinical care setting.
	Glasø, Lars, PhD	Affects and emotional regulation in leader-subordinate relationships.
	Knutsen, Ketil, Dr. philos.	Historier ungdom lever – En studie av hvordan ungdommer bruker historie for å gjøre livet meningsfullt.
	Matthiesen, Stig Berge, PhD	Bullying at work. Antecedents and outcomes.

**2006**

- H Gramstad, Arne, PhD Neuropsychological assessment of cognitive and emotional functioning in patients with epilepsy.
- Bendixen, Mons, PhD Antisocial behaviour in early adolescence: Methodological and substantive issues.
- Mrumbi, Khalifa Maulid, PhD Parental illness and loss to HIV/AIDS as experienced by AIDS orphans aged between 12-17 years from Temeke District, Dar es Salaam, Tanzania: A study of the children's psychosocial health and coping responses.
- Hetland, Jørn, Dr. psychol. The nature of subjective health complaints in adolescence: Dimensionality, stability, and psychosocial predictors
- Kakoko, Deodatus Conatus Vitalis, PhD Voluntary HIV counselling and testing service uptake among primary school teachers in Mwanza, Tanzania: assessment of socio-demographic, psychosocial and socio-cognitive aspects.
- Mykletun, Arnstein, Dr. psychol. Mortality and work-related disability as long-term consequences of anxiety and depression: Historical cohort designs based on the HUNT-2 study.
- Sivertsen, Børge, PhD Insomnia in older adults. Consequences, assessment and treatment.

**2007**

- V Singhammer, John, Dr. philos. Social conditions from before birth to early adulthood – the influence on health and health behaviour.
- Janvin, Carmen Ani Cristea, PhD Cognitive impairment in patients with Parkinson's disease: profiles and implications for prognosis.
- Braarud, Hanne Cecilie, Dr. psychol. Infant regulation of distress: A longitudinal study of transactions between mothers and infants.
- Tveito, Torill Helene, PhD Sick Leave and Subjective Health Complaints.
- Magnussen, Liv Heide, PhD Returning disability pensioners with back pain to work.
- Thuen, Elin Marie, Dr. philos. Learning environment, students' coping styles and emotional and behavioural problems. A study of Norwegian secondary school students.
- Solberg, Ole Asbjørn, PhD Peacekeeping warriors – A longitudinal study of Norwegian peacekeepers in Kosovo.
- H Søreide, Gunn Elisabeth, Dr. philos. Narrative construction of teacher identity.
- Svensen, Erling, PhD Work and health. Cognitive Activation Theory of Stress applied in an organisational setting.

	Øverland, Simon Nygaard, PhD	Mental health and impairment in disability benefits. Studies applying linkages between health surveys and administrative registries.
	Eichele, Tom, PhD	Electrophysiological and Hemodynamic Correlates of Expectancy in Target Processing.
	Børhaug, Kjetil, Dr.philos.	Oppseding til demokrati. Ein studie av politisk oppseding i norsk skule.
	Eikeland, Thorleif, Dr.philos.	Om å vokse opp på barnehjem og på sykehus. En undersøkelse av barnehjemsbarns opplevelser på barnehjem sammenholdt med sanatoriebarns beskrivelse av langvarige sykehusopphold – og et forsøk på forklaring.
	Wadel, Carl Cato, Dr.philos.	Medarbeidersamhandling og medarbeiderledelse i en lagbasert organisasjon.
	Vinje, Hege Forbech, PhD	Thriving despite adversity: Job engagement and self-care among community nurses.
	Noort, Maurits van den, PhD	Working memory capacity and foreign language acquisition.
<b>2008</b>		
V	Breivik, Kyrre, Dr.psychol.	The Adjustment of Children and Adolescents in Different Post-Divorce Family Structures. A Norwegian Study of Risks and Mechanisms.
	Johnsen, Grethe E., PhD	Memory impairment in patients with posttraumatic stress disorder.
	Sætrevik, Bjørn, PhD	Cognitive Control in Auditory Processing.
	Carvalho, Susana Fonseca, PhD	Prevention of bullying in schools: an ecological model.
<b>2008</b>		
H	Brønneck, Kolbjørn Selvåg	Attentional dysfunction in dementia associated with Parkinson's disease.
	Posserud, Maj-Britt Rocio	Epidemiology of autism spectrum disorders.
	Haug, Ellen	Multilevel correlates of physical activity in the school setting.
	Skjerve, Arvid	Assessing mild dementia – a study of brief cognitive tests.
	Kjønniksen, Lise	The association between adolescent experiences in physical activity and leisure time physical activity in adulthood: a ten year longitudinal study.
	Gundersen, Hilde	The effects of alcohol and expectancy on brain function.



