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**The aspect of temporal auditory information for
German vowel length processing in developmental
dyslexia: Behavioural and fMRI Experiments**

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ABBREVIATIONS

AC	anterior commissure
ANOVA	Analysis of Variance
BA	Brodmann Area
BOLD	Blood oxygenation level dependent
BW	Bandwidth
CBF	Cerebral Blood Flow
cf.	confer (<i>latin: for compare</i>)
CVC	Consonant-Vowel-Consonant
EEG	Electroencephalography
e.g.	exempli gratia (<i>latin: for example</i>)
ERP	Event-Related Potentials
et al.	et alii, et aliae, et alia (<i>latin: and others</i>)
etc.	et cetera (<i>latin: and so on</i>)
f	female
fMRI	functional Magnetic Resonance Imaging
FoV	Field of view
FWE	Familii Wise Error
FWHM	Full Width at Half Maximum
GLM	General Linear Model
HRF	Hemodynamic Response Function
Hz	Hertz
i.e.	id est (<i>latin: that means</i>)
IFG	Inferior Frontal Gyrus
ISI	Inter-Stimulus-Interval
L	Left

M	Mean value
m	male
mm	millimetre
MMN	Mismatch Negativity
MNI	Montreal Neurology Institute
MPRAGE	Magnetization Prepared Rapid Gradient Echo
MRI	Magnetic Resonance Imaging
MR	Magnetic Resonance
msec	millisecond
n	number of participants
PC	posterior commissure
PET	Positron Emission Tomography
PFC	Prefrontal Cortex
pp.	pages
Px	Pixel
R	Right
ROI	Region of Interest
RT	Reaction Time
SD	Standard Deviation
sec	second
SPM	statistical parametric mapping
T	Tesla
TE	Echo Time
TR	Time of Repetition
T1 & T2	weighted spin relaxation times for MRI scans
V	Vowel
vs.	versus

1. INTRODUCTION

Reading and writing are one of the most important cultural abilities and enable the access to higher education. We need these abilities in everyday life, they allow us to integrate properly into a community and they are besides speech the most important keys for academic achievements. Only children who know how to read and write properly can profit from attending school and gain the opportunity for a successful school and job career.

The impairment of learning to read (and write) is called *developmental dyslexia* and it is supposed to be the most common learning disability. In Germany approximately five percent of all pupils suffer from this impairment and its consequences (Haffner et al., 1998; Schulte-Körne, 2002). The children have to deal with school, social and mental problems which last till adulthood (Schulte-Körne, 2001). Despite intensive research within this field during the last two decades consensus about the etiological basis of dyslexia is still lacking. The investigation of the underlying principles of this deficit is however crucial in order to understand it better and to create proper, adequate and effective therapeutic approaches.

1.1 Developmental Dyslexia

1.1.1 Definition

Developmental dyslexia is characterized as a specific dysfunction concerning learning to read properly, in spite of average or above-average intelligence and adequate schooling (Shaywitz and Shaywitz, 2005). Furthermore, the reading deficit does not result from sensory deficits (American Psychiatric Association, 1994; Shaywitz, 1998). *Acquired* dyslexia due to neurological diseases, visual deficits or emotional disorders has to be excluded (ICD-10-GM, 2008). Additionally, Tallal (1980) suggests that impairments of the peripheral auditory system as well as motivational deficits have to be ruled out as the cause of developmental dyslexia. The reading problems are very often accompanied by spelling difficulties. Current models of literacy development state that reading and spelling develop jointly, yet out of step with each other. In different phases of literacy development, reading acts as a pacemaker for spelling and vice versa (Frith, 1986). Thus, it can be expected that spelling problems arise as a consequence of the primary reading deficit in dyslexia. Indeed, it was found that dyslexia is characterized by poor spelling abilities (Shaywitz and Shaywitz, 2005). In the international classification system of the world health organization (ICD-10-GM, 2008) the combined reading and spelling impairment is therefore also listed under the same diagnosis code as the isolated reading deficit (F81.0). Only isolated spelling deficits are listed under a separate diagnosis code (F81.1).

Longitudinal studies indicate that reading and spelling problems can be improved with age (Strehlow et al., 1992; Shaywitz et al., 1999). However, developmental dyslexia is a persistent condition rather than a “transient developmental lag” (Shaywitz and Shaywitz, 2005; Svensson and Jacobson, 2006).

The prevalence for developmental dyslexia as reported in literature is, due to the loose definition, quite diverse and ranging between 5 % to 17.5 % (Démonet et al., 2004; Shaywitz, 1998). About 4 % to 8 % of primary school children show specific reading deficits (Lewis et al., 1994; Schulte-Körne, 2002). For the German speaking population it is expected that approximately 6 % to 9 % of all adults show spelling abilities which are inferior to the average spelling abilities of fourth grade pupils (Haffner et al., 1998; Schulte-Körne, 2002).

1.1.2 Reading and spelling deficits

The problems that dyslexics exhibit during reading (aloud) is that words, parts of words or phonemes¹ are exchanged, intermingled, added or completely left out (Schulte-Körne, 2001). Furthermore reading speed, in especially transparent orthographies, is significantly decreased (see Wimmer and Schurz, 2010, for review). Additionally, fixation of letters or words or holding the eye position during the reading process can be impaired (Schulte-Körne, 2001). Dyslexics often complain (Stein, 2001) that letters move around, change place or merge with each other during trying to read. Reversed orders of letter features (e.g. confusing *d* with *b* and *p* with *q*) or neighbouring letters (e.g. in German *ie* instead of *ei*) and anagram errors can be observed. Moreover, the processing and/or maintenance of the information that has been read seems to be impaired as dyslexics often show deficits in reproduction tasks regarding reading content (Schulte-Körne, 2001).

With respect to spelling deficits the following errors are often observed in dyslexia: addition or subtraction of letters, substitution of similar sounding letters or semantic substitution of words, orthographic errors and difficulties writing specific letters (Schulte-Körne, 2002). In German, additionally, specific errors of vowel length marking (Klicpera and Gasteiger-Klicpera, 1998) can be observed.

¹ A *phonem* is the smallest segmental unit of speech sound with meaningful contrast.

Furthermore, children with dyslexia often show bad and effortful handwriting (Nicolson and Fawcett, 1990; Nicolson et al., 2001).

1.1.3 Genesis

The definition of dyslexia² is simply descriptive as, to date, consensus about the etiological basis of dyslexia is still lacking. In general, dyslexia is a very heterogeneous disorder for which numerous causes are proposed in literature. Various theories like for example the *cerebellar theory* (e.g., Bishop, 2002; Nicolson et al., 2001, for review; Stein, 2001), the *magnocellular theory* (e.g., Lovegrove et al., 1980; Stein, 2001; Talcott et al., 1998) or the *rapid temporal processing theory* (e.g. De Martino et al., 2001; Farmer and Klein, 1995, for review; Tallal, 1980, 2000) try to explain the cognitive mechanisms underlying dyslexia (Démonet et al., 2004; Heim et al., 2008). As the latter theory is the theoretical basis of this work it will be explained in more detail in section 1.1.5 (pp. 7-11).

There is, however, agreement that the disorder has a neurobiological (see Démonet et al., 2004; Habib, 2000, for review) and genetic basis (e.g., DeFries 1991; Fagerheim et al., 1999; Fisher and Francks, 2006; Gayán et al., 1999; Pennington et al. 1991; Schulte-Körne, 2001).

Genetic basis: Several family and twin studies (Olson et al., 1989, 1994; Schulte-Körne et al., 1996) indicate familial heredity, though it does not show classical mendelian inheritance. According to Schulte-Körne and colleagues (1996) the probability of the occurrence of another dyslexic in a family where the disorder has already been diagnosed before can be up to 50 % high. Already several regions on

² The terms developmental dyslexia and dyslexia are used synonymously within this thesis. When talking about dyslexia always developmental and not acquired dyslexia is meant.

chromosomes (chromosome 1, 2, 3, 6, 15 and 18) have been identified for carrying genes that affect reading disabilities (see Démonet et al., 2004, for review).

Neurobiological findings: Methods like structural and functional magnetic resonance imaging (MRI) or positron emission tomography (PET) have tried to solve the neurobiological basis of dyslexia. Most studies focused hereby on reading or on phonological processing like verbal working memory tasks or auditory presentation of linguistic or non-linguistic stimuli. Although reading activates a widely distributed network two predominantly left sided posterior pathways are assumed to be crucial for the reading process (Démonet et al., 2004; Shaywitz and Shaywitz, 2004; Steinbrink et al., 2008): the dorsal pathway including temporo-parietal regions, like the supramarginal and angular gyrus, is supposed to develop first. It is responsible for the integration of orthographic, phonological and lexical-semantic information. The ventral pathway runs through occipito-temporal regions like the fusiform gyrus and constitutes a late-developing word form system for automatic word recognition in the visual word form area (VWFA). In a third anterior component comprising the left inferior frontal gyrus (IFG), the information is then recoded into articulatory aspects. The brains' reading system with its three components is shown in figure 1.

Paulesu and colleagues (1996) argue that dyslexia might be a disconnection syndrome, with anterior and posterior reading systems being not as good connected in dyslexics as in normal readers. In their PET study they observed, that dyslexics and controls activated the same brain regions (Broca's area and the temporo-parietal cortex). However, the difference was that dyslexics in contrast to normal readers did not activate these regions in concert and showed a lacking activation of the insula. Shaywitz and colleagues (2001) further suggest a disruption of posterior reading systems in dyslexics. As a consequence the dyslexic brain tries to compensate for that deficit and shifts to ancillary systems like the

anterior regions. On a structural basis hypointense grey matter in left temporal cortex (Brambati et al., 2004; Brown et al., 2001) and decreased fractional anisotropy (FA) in bilateral fronto-temporal and temporo-parietal white matter fibres were found (Klingberg et al., 2000; Deutsch et al., 2005; Steinbrink et al., 2008). This further supports the assumption of a disconnection syndrome in dyslexia. The main finding of fMRI studies with respect to phonological processing is reduced hemodynamic brain activation in especially left sided language networks, like the supramarginal gyrus, in dyslexics as compared to control subjects (Démonet et al., 1996; Démonet et al., 2004; Ruff et al., 2002; Steinbrink et al., 2009). This also indicates a dysfunction of brain regions relevant for reading and spelling. The aspect of auditory temporal processing in the dyslexic brain is highlighted in section 1.2.2 (pp. 15-17).

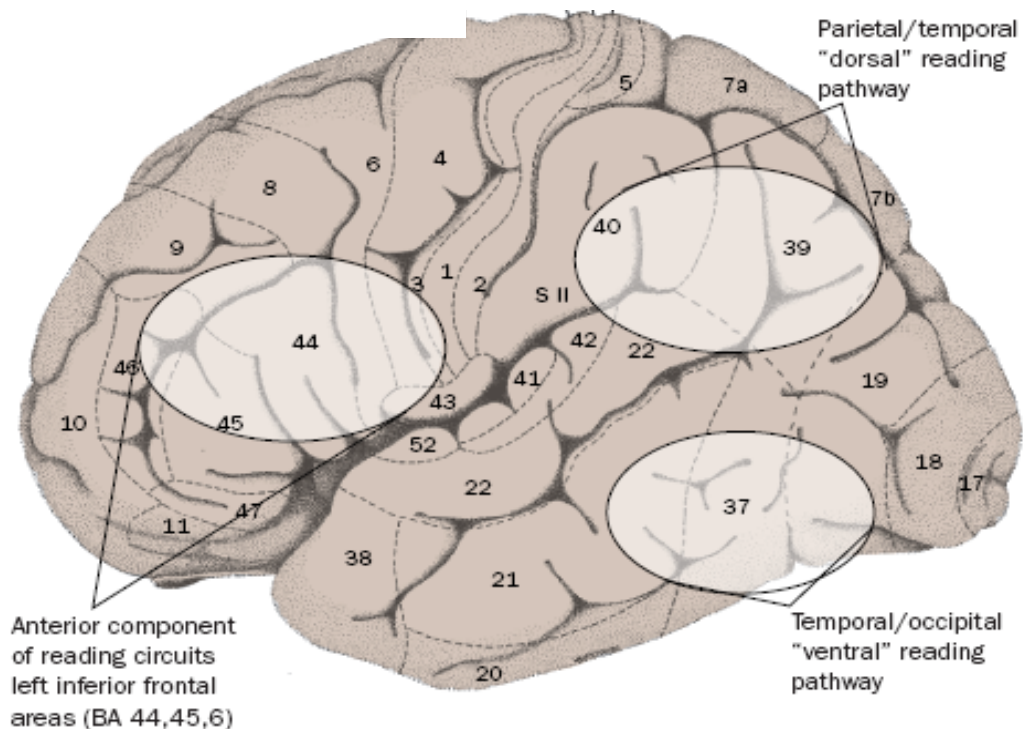


Figure 1: Neural basis of reading

Brain regions of the left cerebral hemisphere involved in reading and in which abnormal responses in neuroimaging studies were reported in adults with developmental dyslexia (taken and modified from Démonet, Taylor and Chaix, 2004; The Lancet, 363, page 1455).

1.1.4 The core symptom

To date, it is still unclear whether there is in fact one and only one core deficit in dyslexia (Aaron et al., 1999; Heim et al., 2008; Lachmann and van Leeuwen, 2008). On the behavioural level, dyslexia is characterized by phonological deficits (Ramus et al., 2003; Vellutino et al., 2004; Wagner and Torgesen, 1987). These deficits have been found for *phonological recoding in lexical access*, as assessed by rapid picture naming (Denckla and Rudel, 1976; Fawcett and Nicolson, 1994; Swan and Goswami, 1997a), in *phonological awareness*, that is, the ability to consciously access and manipulate the sound units of language (Bradley and Bryant, 1983; Bruck, 1992; Elbro and Jensen, 2005; Swan and Goswami, 1997b), and in *phonological short-term memory*, as assessed by immediate serial recall of unrelated verbal items such as digits, words, or by nonword repetition (Jeffries and Everatt, 2004; Nelson and Warrington, 1980; Roodenrys and Stokes, 2001; Steinbrink and Klatte, 2008). Developmental dyslexia is also associated with deficits in the *perception of phonemes*, often assessed in categorical perception tasks (Adlard and Hazan, 1998; Godfrey et al., 1981; Manis et al., 1997; Mody et al., 1997). All of these aforementioned abilities are accomplished on the basis of phonological representations. Thus, the phonological deficit in dyslexia is assumed to result either from an underspecification of these representations (Adlard and Hazan, 1998; Boada and Pennington, 2006; Elbro and Jensen, 2005; Manis et al., 1997; Mody et al., 1997; Swan and Goswami, 1997a, b) or from a suboptimal access to these phonological representations (Ramus and Szenkovits, 2008).

1.1.5 The auditory temporal processing deficit theory

A debate that is still going on in the scientific community is whether phonological deficits constitute the core deficit of developmental dyslexia (Snowling, 2000; Stanovich, 1988) or whether they are secondary to more general auditory

processing deficits (Ahissar et al., 2000; Lachmann et al., 2005; Richardson et al., 2004). The *auditory temporal processing deficit hypothesis* (Tallal, 1980), for instance, argues that phonological deficits in dyslexia are secondary to low level auditory temporal processing impairments which affect the perception of acoustic elements characterized by rapid transitions or short durations. According to this view, the basic temporal processing impairment leads to an inability to integrate sensory information entering the central nervous system in rapid succession. This causes a cascade of effects, starting with disruption of the normal development of the phonological system, leading to incomplete or impaired representations in this phonological system and subsequent failure to read normally (Tallal et al., 1993).

Using non-speech stimuli, a number of psychophysical studies confirmed the hypothesis of an auditory temporal processing deficit in dyslexic children (Cohen-Mimran and Sapir, 2007; Heiervang et al., 2002; van Ingelhem et al., 2001) and adults (Ben-Artzi et al., 2005; Laasonen et al., 2001; see Farmer and Klein, 1995, for review). Others, however, failed to find such evidence (Breier et al., 2003; Schulte-Körne et al., 1998).

Some studies used non-linguistic material in order to investigate temporal processing as well as linguistic material to investigate phonological processing in one and the same sample. These studies either found that temporal processing deficits are not related to phonological processing impairments in dyslexia (Bretherton and Holmes, 2003; Nittrouer, 1999) or that phonological deficits can appear in the absence of temporal processing deficits (Boets et al., 2007; Ramus et al., 2003; White et al., 2006) and are thus in favour of the phonological theory of dyslexia. For testing the auditory temporal processing deficit hypothesis these studies used tasks such as temporal order judgement or gap detection, which are the classical tasks that were also used by Tallal and colleagues when first describing this deficit. To test the phonological processing deficit hypothesis, tasks

such as phoneme deletion, non-word repetition or rapid automatized naming (RAN) were used in order to measure phonological awareness, phonological short-term memory or phonological recoding in lexical access, respectively. If the authors, then, found group differences for the latter set of tasks but not for the former, they concluded that auditory processing deficits are not the core deficit of developmental dyslexia. This interpretation, however, does not consider that phonological compared to temporal processing tasks do not only differ in the linguistic nature of the stimuli (linguistic vs. non-linguistic) but also in complexity. Stimulus and task complexity are much higher in phonological conditions as compared to the auditory ones. This might explain why dyslexics showed deficits in the phonological conditions only.

One way to minimize these methodological confounds is to study how the temporal aspects of speech signals are processed. To date, few studies have used such an approach. Reed (1989) found that dyslexic children were impaired in the identification of the order of stop consonant syllables when these were presented with short inter stimulus intervals (ISIs). However, dyslexics' performance was not impaired when vowels were used instead of stop consonants. This pattern of results was attributed to specific difficulties in processing very brief auditory cues in dyslexia (Reed, 1989). Rey et al. (2002) found evidence for a temporal processing deficit in dyslexia using temporal order judgement tasks in which consonant clusters were presented. Dyslexics' performance was poorer than that of controls. When the stimuli were artificially slowed, however, dyslexics' performance improved to reach the normal controls' level.

McAnally and colleagues (1997) compared the performance of dyslexic children and controls in a consonant-vowel-consonant (CVC) syllable identification task. The syllables were stretched or compressed within the time domain. In both time manipulated conditions response accuracy was found to have deteriorated as

compared to the baseline condition. Furthermore, the authors found no group difference in any of the conditions, including baseline. Still, these results cannot be taken as evidence against the temporal processing deficit hypothesis of dyslexia. The deterioration in accuracy suggests, rather, that modifying the syllables in the time domain simply degraded the auditory signal, which made it more difficult to match the perceived phoneme string to an appropriate long-term representation. There are two major problems with the method used by McAnally et al. (1997): first, the whole CVC syllables were changed in the time domain leading to stimuli consisting of sounds which did not correspond to the phoneme system of the language under investigation. Second, these syllables were used in an identification task requiring a comparison of perceived phoneme strings with their long-term representations which, in turn, did not correspond to the presented stimuli.

Another way to resolve the addressed problems would be, to use stimuli with comparable complexity and equivalent tasks to test phonological as well as temporal processing. Indeed, recent studies by Vandermosten and colleagues (2010, 2011) tried to do this. They wanted to clarify if the behavioural deficits observed in dyslexia are speech specific or not, and furthermore, if they originate from deficient temporal processing of the signal or from a broader range of spectro-temporal processing deficits. For that purpose they created non-speech stimuli which were comparable in acoustic complexity to their speech stimuli by spectrally rotating the speech stimuli. This resulted in stimuli which were not perceived as speech but showed the same spectro-temporal complexity as the speech stimuli. To investigate phonological vs. temporal processing, stimuli that exploit temporal cues (/ba/-/da/) were contrasted with stimuli carrying non-temporal, steady-state cues (/u/-/y/). In a categorical perception task they could show that dyslexic children (Vandermosten et al., 2011) and adults (Vandermosten et al., 2010) are characterized by an auditory temporal processing deficit that is not speech specific.

Dyslexics performed worse on both speech and non-speech stimuli with rapidly changing acoustic cues but were unimpaired on the steady-state speech and non-speech conditions. The authors solved the complexity problem between speech and non-speech stimuli in a very elegant way. However, the comparability problem between spectral or phonological and temporal stimuli remains. The utilized temporal and non-temporal speech stimuli still differ in complexity, as CV combinations are contrasted to single vowels. Furthermore, the temporally changing stimuli (/ba/-/da/) differed not only in their temporal but also in spectral dimensions. Many previous studies investigated the temporal processing deficit hypothesis with exactly such CV stimuli because the acoustic difference between /ba/ and /da/ lies within the transition of the second formant (F2). For /ba/ the formant is rapidly rising, for /da/ it is rapidly falling. However, this rapid change is automatically accompanied by spectral changes of the speech signal, which makes exact conclusions problematic.

To summarize, there is a general agreement that phonological processing abilities are impaired in developmental dyslexia. The underlying cause of this impairment is, however, hotly debated. Do deficits in auditory temporal processing hinder the normal development of the phonological system, as argued by Tallal (1980, 2000)? Do phonological impairments generate from an interaction of temporal auditory processing deficits and deficits in other parameters of auditory processing, such as frequency discrimination (Ahissar et al., 2000)? Or is a phonological deficit per se the core symptom and auditory processing deficits secondary (Ramus et al., 2003; Boets et al., 2007)? Empirical results remain inconclusive. Reasons for the contradicting findings of studies include methodological differences and restrictions such as incompatibility of stimuli and task parameters between the linguistic and the non-linguistic conditions.

1.2 Auditory processing

1.2.1 Hemispheric asymmetry of auditory processing

Recent research supports the notion of a functional hemispheric asymmetry for auditory temporal processing in healthy subjects. The left hemisphere is supposed to process information in shorter temporal integration windows (25-50 msec.) and the right in longer ones (150-250 msec.; Nicholls, 1996; Ivry and Robertson, 1998; Poeppel, 2001; Hickok and Poeppel, 2000, 2004; Zatorre et al., 2002; Johnsrude et al., 1997; Ackermann et al., 2001; Ackermann and Riecker, 2004; Riecker et al., 2008). The exact nature of the mechanisms underlying this hemispherical asymmetry is, however, still discussed. Zatorre and colleagues propose that auditory cortical areas differ in their relative sensitivity to temporal and spectral features of sounds (Zatorre and Belin, 2001; Zatorre et al., 2002; Zatorre and Gandour, 2008): the left hemisphere preferentially processes temporal features, whereas the right hemisphere preferentially processes spectral features. Shorter integration times provide higher temporal resolution at the expense of lower spectral resolution, whereas longer temporal windows provide lower temporal but higher spectral resolution. Thus, hemispheric differences might reflect a higher specialization of the left hemisphere concerning rapid temporal processing, and of the right hemisphere for fine and subtle extraction of the spectral information of the speech signal. This principle is illustrated exemplarily in figure 2 as proposed by Poeppel (2001). Tallal and her colleagues (Schwartz and Tallal, 1980; Tallal et al., 1993; Fitch et al., 1997) argue, alternatively, that the hemispheric specialization is secondary to left hemispheric specialization for the processing of rapidly changing acoustic information.

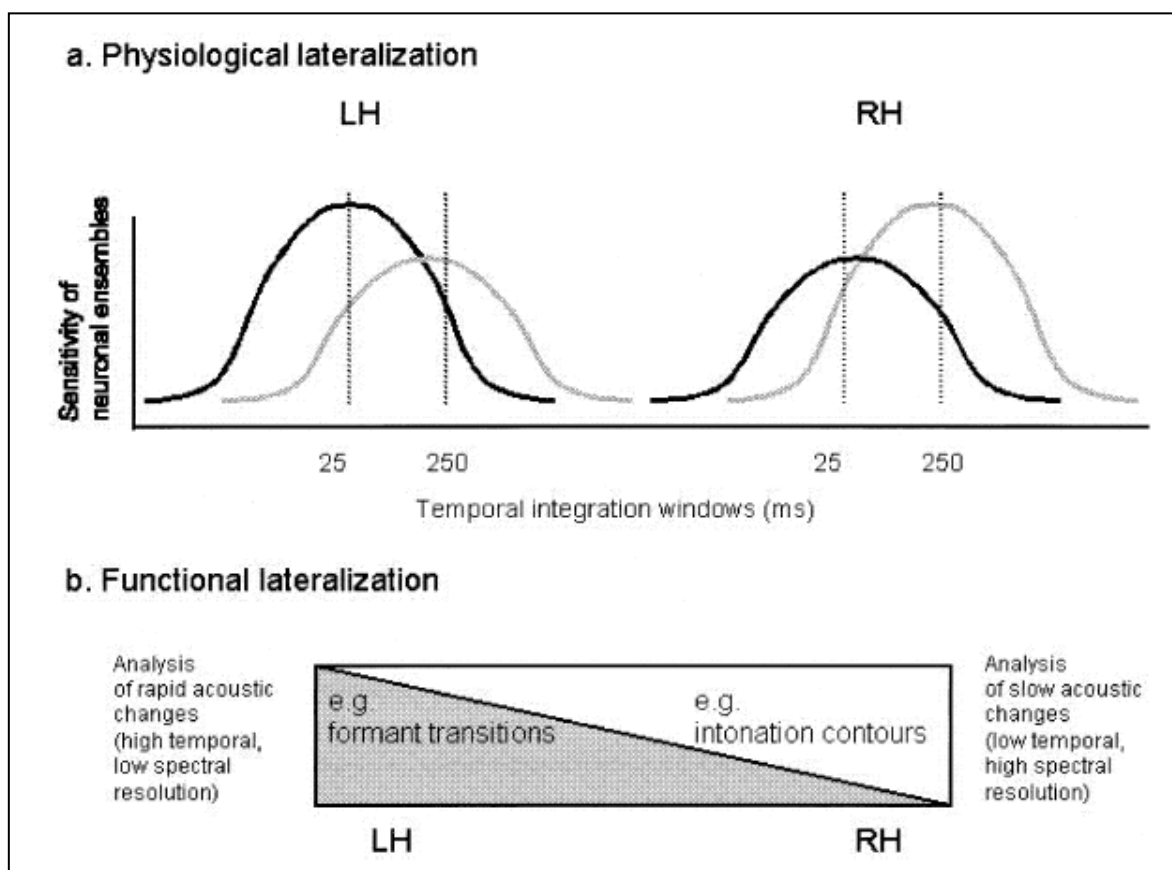


Figure 2: Hemispheric asymmetry of auditory processing

The upper panel shows possible distributions of neuronal ensembles with different temporal integration times. In the left hemisphere (LH) cell ensembles with a preference for short integration times dominate (dark line); vice versa in the right hemisphere (RH) cell ensembles with a preference for long integration times dominate (bright line). The lower panel illustrates how such physiological sensitivities may be associated with preferences in processing one or the other type of information (taken from Poeppel, 2001; *Cognitive Science*, 25, page 689).

The empirical evidence within this controversy is rather mixed. A number of brain imaging studies in which non-speech stimuli were used, support the view that the left hemisphere preferentially processes temporal information, while the right hemisphere preferentially processes spectral information (Jamison et al., 2006; Schönwiesner et al., 2005; Zatorre and Belin, 2001). A very recent fMRI study specifically investigated the role of the right auditory cortex in spectral processing

and found evidence that the right hemisphere provides finer pitch resolution than the left does (Hyde et al., 2008).

The majority of brain imaging studies on hemispheric specialization in auditory processing focused on neural correlates of temporal processing. Many of these studies revealed that the left hemisphere preferentially processes rapid temporal features of non-speech stimuli (Belin et al., 1998; Ackermann et al., 2001; Boemio et al., 2005). A recent study by Abrams and colleagues (2008) found that slow temporal features in speech are preferentially processed by the right hemisphere. Interestingly, various brain imaging studies using both speech and non-speech stimuli for studying auditory temporal processing show that similar cortical areas are activated in speech and non-speech temporal auditory processing and confirm the specialization of the left hemisphere for rapid temporal processing (Fiez et al., 1995; Zaehle et al., 2004, 2008). Others, however, come to the conclusion that either the dominance of the left hemisphere for rapid temporal processing is restricted to speech sounds (Shtyrov et al., 2000) or fail to find any left hemisphere advantage for neither speech nor non-speech stimuli (Joanisse and Gati, 2003). As for the behavioural studies also here, one has to keep in mind that often the utilized speech and non-speech stimuli can not be compared due to differing complexity thus making clear interpretations difficult.

To summarize, to date the role of spectral and temporal information on hemispheric asymmetries in auditory processing is not completely understood. Moreover, the question whether auditory processing of non-linguistic stimuli recruits the same neural substrate as auditory processing of linguistic stimuli needs further consideration.

1.2.2 Auditory processing in the dyslexic brain

By measuring neural correlates of cognitive processes in experimental designs, neurophysiological methods like electroencephalography (EEG) and magnetoencephalography (MEG) as well as brain imaging techniques like functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) help to uncover the cognitive deficits underlying developmental dyslexia. Event related potential (ERP) and MEG studies suggest that the neural processing of rapid auditory stimuli is disrupted in dyslexia (Kraus et al., 1996; Nagarajan et al., 1999; see also Bishop, 2007, for review). An ERP study by Baldeweg et al. (1999) found, however, that mismatch negativity (MMN) potentials to changes in tone frequency are abnormal, while responses to changes in tone duration are unimpaired. A recent ERP experiment by Corbera and colleagues (2006) revealed an opposite pattern, i.e. abnormal MMN amplitudes for duration of non-phonological sounds, but no abnormalities for pitch processing in dyslexia. Also, ERP studies investigating speech vs. non-speech auditory processing in dyslexia came to inconsistent results. Some studies found diminished MMN in dyslexics for non-speech, but normal-like MMN for speech stimuli (Corbera et al., 2006). Others, in turn, found the opposite, i.e. diminished MMN for speech but not for non-speech stimuli in dyslexics (Schulte-Körne et al., 1998). Yet, others found diminished MMN in dyslexics for both categories of stimuli (Lachmann et al., 2005).

Although many PET and fMRI studies report abnormal activation patterns for phonological processing in dyslexia (see Habib, 2000; McCandliss and Noble, 2003; and Ligges and Blanz, 2007, for review), to date only few studies have investigated low-level auditory processing in dyslexia using functional brain imaging techniques. To the best of contemporary knowledge no single functional brain imaging study

investigated spectral auditory processing in dyslexia. Concerning temporal auditory processing, functional neuroimaging studies with adults (Temple et al., 2000) and children (Gaab et al., 2007), revealed disruption of hemispheric specialization for rapid relative to slow acoustic stimulation with non-linguistic stimuli in dyslexia: a specifically increased hemodynamic response in regions of the left prefrontal cortex, more specifically in left Brodmann Areas (BA) 46/47 and 9/10 along the middle and superior frontal gyrus, as well as the left inferior frontal gyrus (IFG), for rapid in contrast to slow stimuli, was observed in normal controls but could not be found in dyslexics. Ruff and collaborators (2002) measured implicit categorical perception of phonemes using normal and slowed down stimuli. Interestingly, in dyslexics, activations in the left frontal cortex (anterior Broca's area 44/45) were increased for slowed down speech stimuli as compared to speech stimuli at a normal rate, whereas the reverse effect was found for controls. An fMRI study by Steinbrink et al. (2009) investigated temporal auditory processing in dyslexia using both linguistic and non-linguistic stimuli. Dyslexic adults and age-matched controls passively listened to click and syllable trains presented at six different frequency rates ranging from 1 to 9 Hz. The anterior insula was identified as an important neural substrate of temporal auditory processing. Dyslexics showed overall reduced activation of the insular region in both the linguistic and the non-linguistic condition, supporting the notion that auditory processing is impaired in developmental dyslexia. Furthermore, controls showed rate-dependent hemodynamic activation of the left and right insula in both conditions. In dyslexics, however, this rate-dependent activation of the insula was restricted to the non-linguistic condition only. As syllables and clicks do not only differ in linguistic content, but also in stimulus complexity, it remains unclear if this result should be interpreted as evidence for a speech-specific temporal auditory processing deficit in dyslexia.

To summarize, all fMRI studies on auditory temporal processing in dyslexia indicate that the sensitivity to rapid relative to slow auditory stimuli in the left frontal cortex is disrupted. Neurophysiological studies, in contrast, are not that consistent. Future research has to clarify if neural correlates of temporal auditory processing differ for non-speech versus speech stimuli. Moreover, functional brain imaging studies investigating specifically spectral auditory processing in dyslexia are needed to further clarify if differing brain regions and hemispheres are recruited for the processing of temporal and spectral auditory information.

In order to do that in a proper way, stimuli of comparable complexity and difficulty and stimuli which can be used to investigate both temporal and spectral processing are needed. In the German language this can be realized by means of the German vowel system, which is explained in the next section.

1.3 The German vowel system

The German vowel system is particularly suitable for the study of auditory processing in dyslexia, as it can be used to study phonological as well as temporal and spectral processing within the same phoneme category. In German, there are fourteen vowel monophthongs that can be grouped into seven pairs, the members of which differ exclusively with respect to tenseness (tense vs. lax; Wiese, 1996) or, synonymously, vowel length (long vs. short; Lühr, 2000). For example, the vowels within the spoken word pairs *Schiff* (/ʃɪf/, [ship]) versus *schief* (/ʃi:f/, [askew]) or *kann* (/kan/, [can]) versus *Kahn* (/ka:n/, [barge]) differ in vowel length. All seven German long-short vowel pairs grouped according to vowel height³ are summarized in table 1.

Table 1: The German vowel pairs grouped according to vowel height.

High vowel pairs		Mid vowel pairs		Low vowel pairs	
long/tense	short/lax	long/tense	short/lax	long/tense	short/lax
/i:/	/ɪ/	/e:/	/ɛ/	/a:/	/a/
/y:/	/ʏ/	/ø:/	/œ/		
/u:/	/ʊ/	/o:/	/ɔ/		

The long and the short vowel of a pair differ in duration. Strange and Bohn (1998) performed acoustical analyses of the seven German long-short vowel pairs spoken in CVC syllables. They recorded the syllables either presented in citation form or embedded as a pseudo-word into sentences. Absolute durational differences

³ Vowel height corresponds to the tongue position in the mouth during articulation of the specific vowel.

between the long and short vowel of a pair ranged in citation form from 45 to 106 msec ($M = 69$ msec) and in the embedded condition from 27 to 77 msec ($M = 35$ msec). The temporal differences between long versus short German vowels overlap with the time window for which Tallal and Piercy (1975) found processing deficits in children with specific-language-impairment. As compared to controls these children were impaired in the discrimination of both English vowels and consonants when the discernible components were of brief (43 msec) duration, but unimpaired when they were 95 msec or longer. This indicates that the temporal differences between long versus short German vowels are in an appropriate range for the investigation of auditory temporal processing.

1.3.1 Perception of vowel length in German

The two vowels of a German long-short vowel pair do not only differ in duration (quantity), but also in terms of their spectral information (quality). The relevance of durational versus spectral information for vowel length perception has been the topic of several *identification* studies (Sendlmeier, 1981; Strange and Bohn, 1998; Weiss, 1974). The authors found that the influence of these two cues on vowel identification depends on vowel height (high vowels: /i:/, /ɪ/, /y:/, /ʏ/, /u:/ and /ʊ/; mid vowels: /e:/, /ɛ/, /ø:/, /œ/, /o:/ and /ɔ/; low vowels: /a:/ and /a/). To identify high vowels, listeners rely more on spectral than on durational information. With decreasing vowel height, the opposite pattern emerges. To identify low vowels, listeners rely more on duration than on spectral information.

Regarding vowel length *discrimination*, the relevance of spectral and temporal cues was, to the best of contemporary knowledge, investigated in only one study: Bohn and Polka (2001) found that German adults and even infants were able to use spectral information to discriminate vowels. The removal of durational information

degraded discrimination performance only selectively. However, only two vowel pairs in their study differed in vowel length (/e/ - /ɛ/ and /o/ - /ʊ/) but these differed additionally in vowel height. Thus, the specific contribution of temporal versus spectral cues to discrimination performance remains unclear.

1.3.2 Perception of vowel length in dyslexia

To date, little is known about the relevance of vowel length perception for disorders of reading and spelling. Correct spelling of vowel length is, however, a major issue in German orthography (Klicpera and Gasteiger-Klicpera, 1998). In German orthography, vowel length is not marked by the vowel letter itself (as it is the case in Finnish), but by the letters following the vowel. Short vowels are, for example, often marked by two following consonants (e.g., Stall, /ʃtal/, [barn]), whereas a typical way to mark a long vowel is to add a “silent h” (e.g. Stahl, /ʃta:l/, [steel]). Thus, the ability to perceive vowel length helps deducing the regularities of German orthography. Indeed, results from a behavioural study indicate that in German, spelling disorders at least might be characterized by deficits in the perception of vowel length: Landerl (2003) used a vowel length categorization task in which word and non-word stimuli were presented orally to ten year old German-speaking poor spellers and age-matched controls. Poor spellers performed less accurately and consistently slower than controls. These results suggest that deficits in vowel length perception might be one causal factor for spelling disorders and thus for dyslexia in German.

Quite some intervention programs therefore include vowel length exercises in their training. In a German orthographic spelling training by Schulte-Körne (Marburger Rechtschreibtraining; Schulte-Körne und Mathwig, 2007) vowel length perception

is an important key aspect which is trained at the very beginning of the program as it forms the basis for the following orthographic rules.

To summarize, long (tense) and short (lax) German vowels differ not only in duration, but also with respect to spectral information. In vowel length perception, both kinds of information are used. The impact of temporal versus spectral cues for vowel length identification depends on vowel height. The relevance of these acoustic cues for vowel length discrimination in general and in developmental dyslexia in particular is still an unresolved issue and needs further consideration in empirical research.

1.4 Aim of the current work

The aim of the current study is to investigate phonological and temporal processing in developmental dyslexia using German vowels in a vowel length discrimination task. By means of functional MRI this study, additionally, tries to resolve the neural correlates of temporal auditory processing in general and of temporal auditory processing in developmental dyslexia.

Importantly in contrast to previous studies, the same task and stimuli with same linguistic content and comparable complexity are used to assess both phonological as well as temporal auditory processing. As vowel length is phonemic in German, the discrimination of natural German vowels is a phonological task. This task is performed on the basis of temporal as well as spectral information. To specifically test temporal auditory processing, spectral information that differentiates long and short German vowels has to be kept constant, which was realized in this study. As a consequence, participants are forced to discriminate vowel lengths purely on the basis of temporal cues. Response accuracies as well as task specific hemodynamic brain activation of the phonological versus temporal vowel length discrimination task will be analyzed and compared between groups.

The obtained findings can give us new insights on the relevance of spectral versus temporal cues for vowel length processing in German. Previous studies have investigated this question using identification tasks, but no study has yet systematically explored the relevance of temporal versus spectral cues for vowel length discrimination. Furthermore, the results can help us to answer the question of a temporal auditory processing deficit in dyslexia on a behavioural as well as neural level, which might have diagnostic and therapeutic consequences in this field.

The questions that are tried to be resolved by this work are: (a) Do adolescents and young adults show deficits in temporal auditory processing as claimed by Tallal (1980) and colleagues, also when task and stimuli complexity are held constant? (b) Which brain regions are involved in temporal auditory processing and is that accompanied with lateralization effects? (c) Can differing hemodynamic brain activations be observed in the respective brain regions in case of temporal auditory processing deficits in dyslexia and how is this difference characterized?

The hypotheses with respect to the raised questions are: If dyslexics have problems with rapid temporal processing one would expect, the dyslexic participants of this study to perform inferior compared to control subjects on the temporal conditions. Depending on the degree of impairment maybe even the performance on the phonological condition might be degraded. Furthermore, a negative correlation between discrimination performance and degree of impairment is expected, with highly affected dyslexics performing worse on the discrimination task. On the neural level one would hypothesize, in accordance with previous studies, left hemispheric processing for rapid temporal stimuli in healthy control subjects. In the dyslexic group such lateralization effects might be lacking. In general, the task specific hemodynamic activation of dyslexics is expected to be decreased compared to controls. Furthermore, one would hypothesize a positive correlation between discrimination performance and brain activation as well as a negative correlation between degree of impairment and hemodynamic activation.

The approach used in this study to address phonological as well as temporal processing within the same task by using experimental stimuli that do not differ in their linguistic content and that show comparable complexity, is unique and overcomes methodological confounds related to task and stimuli that hampered unequivocal interpretation of the results of former studies.

2. EXPERIMENT 1: BEHAVIOURAL EXPERIMENT⁴

2.1 Methods and Material

2.1.1 Participants

Twenty participants diagnosed with developmental dyslexia (15 males) and twenty control participants (14 males) matched with respect to intelligence, sex and age took part in this study. Participants were adolescents and young adults aged between 14.3 and 23.7 years ($M = 17.9$ years, $SD = 2.7$ years) and were monolingual native speakers of German. Due to the intended fMRI experiment all subjects, additionally, had to be right-handed as determined by means of the Edinburgh Handedness Inventory (lateralization index > 70 %; Oldfield, 1971). None of the participants reported a history of neurological diseases, head injury, psychiatric disorders or hearing problems. Informed consent was obtained in line with the Institutional Review Board of the University of Ulm (Appendix A).

Participants with dyslexia had been diagnosed in primary school. They had a documented history of both reading and spelling difficulties across their entire school career persisting to date. In order to validate the previously given diagnoses, all participants, dyslexics and controls, were tested again up to four weeks before the experiment. Inclusion in this study required an average or above average non-verbal intelligence as measured by the Culture Fair Intelligence Test (German version, Weiß, 1997). All participants were given standardized tests of reading and spelling. For the evaluation of reading abilities, a German reading test for adults was used (Schulte-Körne, 2001; Appendix B) measuring reading time

⁴ Originally published in the journal “Reading and Writing”*: Groth K, Lachmann T, Riecker A, Muthmann I, Steinbrink C: Developmental dyslexics show deficits in the processing of temporal auditory information in German vowel length discrimination. Reading and Writing 24: 285-303 (2011). *All rights reserved by Springer Science and Business Media.

and errors for real words and pseudo-words. For all four reading measures dyslexic participants had to score below two standard deviations of the mean performance of the controls. Spelling was measured by means of a standardized German spelling test for adults (Rechtschreibungstest RT, Kersting and Althoff, 2004; Appendix C). To qualify as dyslexic, participants had to score below one standard deviation of the mean performance of the reference population, while control participants had to show average or above average spelling skills. The test analysis shows very poor spelling skills in the dyslexic group (percentage rank < 16) and average or above average spelling skills in the control group (percentage rank > 31). In total, the diagnostic tests were performed with 21 dyslexics and 23 controls. One dyslexic had to be excluded from the study because of an average spelling score. Three controls had to be excluded due to substandard reading or spelling performance. The remaining 20 dyslexics and 20 controls are those participating in the study (see table 2 for group characteristics and differences).

Table 2: Group characteristics and test scores for Dyslexics and Controls.

	Dyslexics ($n = 20$)		Controls ($n = 20$)		p^a
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
Age (years)	17.94	2.78	17.92	2.77	.981
Non-verbal IQ	112.75	16.35	117.85	10.92	.253
<i>Real-word reading</i>					
Errors (max. 48)	4.30	2.56	0.45	0.61	$<.001$
Reading time (sec.)	59.90	15.78	32.50	5.81	$<.001$
<i>Pseudo-word reading</i>					
Errors (max. 48)	11.05	5.96	2.95	1.93	$<.001$
Reading time (sec.)	115.20	38.49	67.05	13.95	$<.001$
<i>Spelling</i>					
Errors (max. 60)	40.70	8.20	12.80	6.88	$<.001$

Note: ^a t - test for independent samples.

2.1.2 Experimental Stimuli

Stimulus generation: In Section 1.3 (pp. 18-21) the fourteen German vowels that can be grouped into pairs, which differ exclusively with respect to vowel length, were introduced. All these fourteen vowels were used to create CVC (consonant-vowel-consonant) pseudo-word syllables of the following two formats: /fVp/ and /nVp/ (V = vowel). Two different onset consonants were chosen to avoid monotony and to assure the participants' attention during the task. Furthermore the onset consonants /f/, /n/ and the offset consonant /p/ were selected because: (1) a combination of these consonants with all fourteen vowels created real non-words, which was intended in order to avoid lexical or semantic processing during syllable discrimination; (2) these CVC pseudo-words were legal phoneme strings according to German phonotactic rules; (3) for the subsequent vowel manipulation consonant combinations were needed which enable a good identification and extraction of the vowel in the mid portion of the syllable. For that purpose especially fricatives and plosives are suitable as can be seen in figure 3, where exemplarily a spectrogram⁵ of the syllable “/fa:p/” is displayed. Here the vowel portion is very good discernable and can be easily delineated from the bordering consonants.

Syllables were spoken embedded in a sentence by a female trained speaker, with normal speaking rate and without stress. The distance between the speaker and the microphone (TAKSTAR SM-1A; Takstar Electronics Co., Guangdong, China) was about 10 cm in order to guarantee consistent sound pressure.

⁵ A spectrogram illustrates in a three dimensional way the intensity of a speech signal at given points in time within the spectrum of frequencies. The vertical axis indicates the frequency range, the horizontal axis the temporal dimension. The intensity of the signal (energy) within a given frequency range is displayed via the intensity of the grey/black scale (Clark & Yallop, 2002).

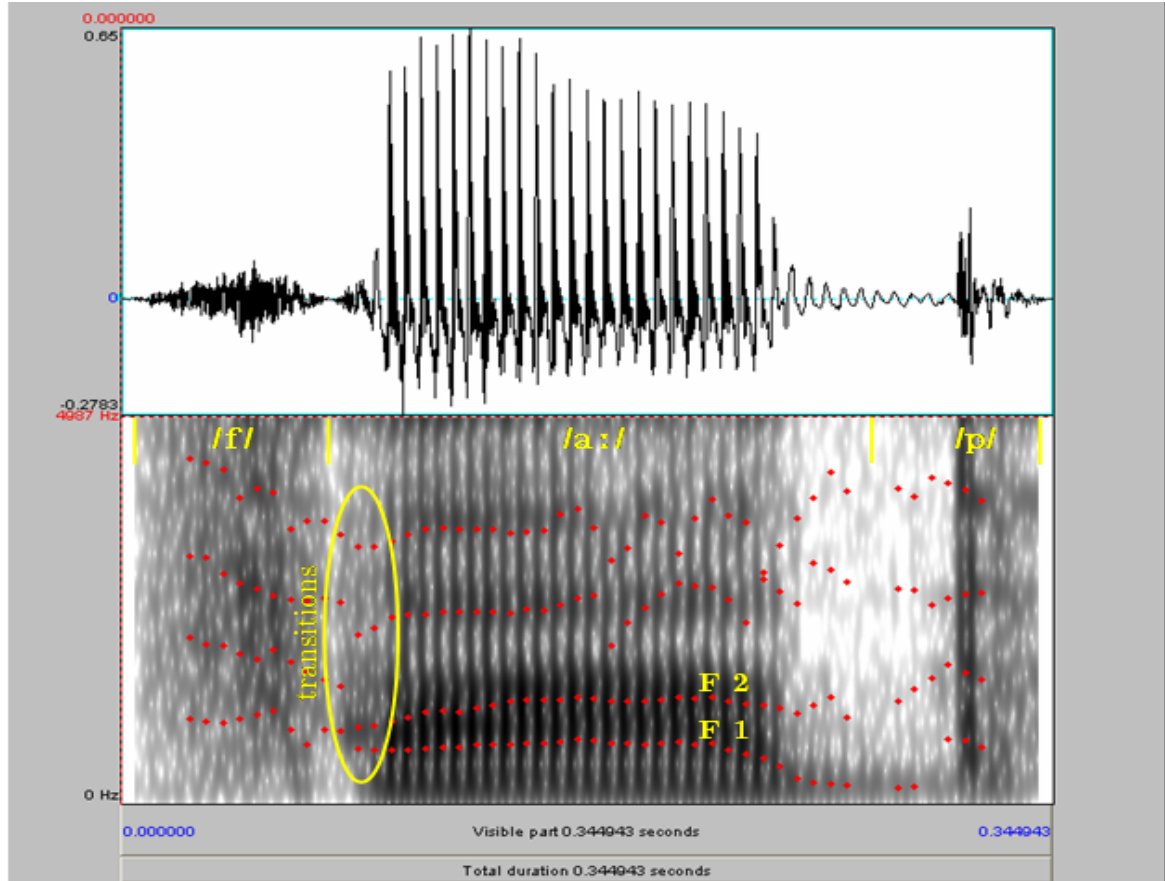


Figure 3: Oscillogram and spectrogram of the pseudo-word syllable “/fa:p/”.

The oscillogram is shown in the upper half, the spectrogram in the lower half of the figure. The phonemes of the syllable and its approximate boundaries are marked in yellow with the according IPA-symbols. The transitions (the transit from /f/ to /a/) where faster formant movements can be observed are indicated via the yellow ellipsis. Darker areas indicate frequency ranges with higher intensity. Here especially the characteristic formants F1 and F2 show stronger intensity and indicate the type of vowel.

To ensure relatively constant pitch over the whole stimulus set, an anchor stimulus was presented to the speaker prior to the recording of each pseudo-word. Recording was performed in a sound-attenuated room utilizing Adobe Audition 1.5 (Adobe Systems Incorporated, San Jose, CA., USA) with a sampling rate of 44 kHz and a resolution of 16 bit.

The best samples of syllables were then selected. In order to assure that the chosen syllables fall within the aforementioned CVC category boundaries, ten adults (lab members) naïve to the study purpose, were asked to perform an identification task.

Syllables were presented via headphones and the participants were instructed to write them down in exactly the way they were perceived, using the orthographic conventions of German vowel length marking (e.g., “fahp or fap” for /fa:p/ and “fapp” for /fap/). If more than 20% of the judgements for a particular syllable did not fit into the intended category, this syllable was replaced by an alternative stimulus for which the procedure was repeated. This was the case in three of the 28 syllables: Two, because more than 20% of the listeners marked vowel length or identity incorrectly, and one, because the consonantal onset was systematically misinterpreted by the whole sample. In the following, we will refer to the natural vowels used in our study as described above as *original or natural vowels/stimuli*.

Stimulus manipulation: In order to address phonological as well as temporal processing within the same task, with experimental stimuli that do not differ in their linguistic content and that show comparable complexity, a second stimulus set had to be generated. This was implemented by manipulating the vowel lengths of the 28 original stimuli. The generation of this second stimulus set was structured in the following way: (1) The length of each vowel in each original CVC-syllable was measured. For this purpose, only the steady-state phase of the vowels was used. To visualize the procedure the spectrogram of the pseudo-word syllable “/fa:p/” is shown in figure 4 indicating the steady-state phase of the vowel /a:/ for its vowel length determination. Transitions were not considered, as the perceived manner of syllable-initial stop consonant shifts from stop to glide when formant transitions are lengthened (Borden, Harris, & Raphael, 1994; Mody et al., 1997). Vowel length was identified by visual inspection of spectrograms (formant movements) and waveforms using the phonetics program “Praat” (Boersma & Weenink, 2005).

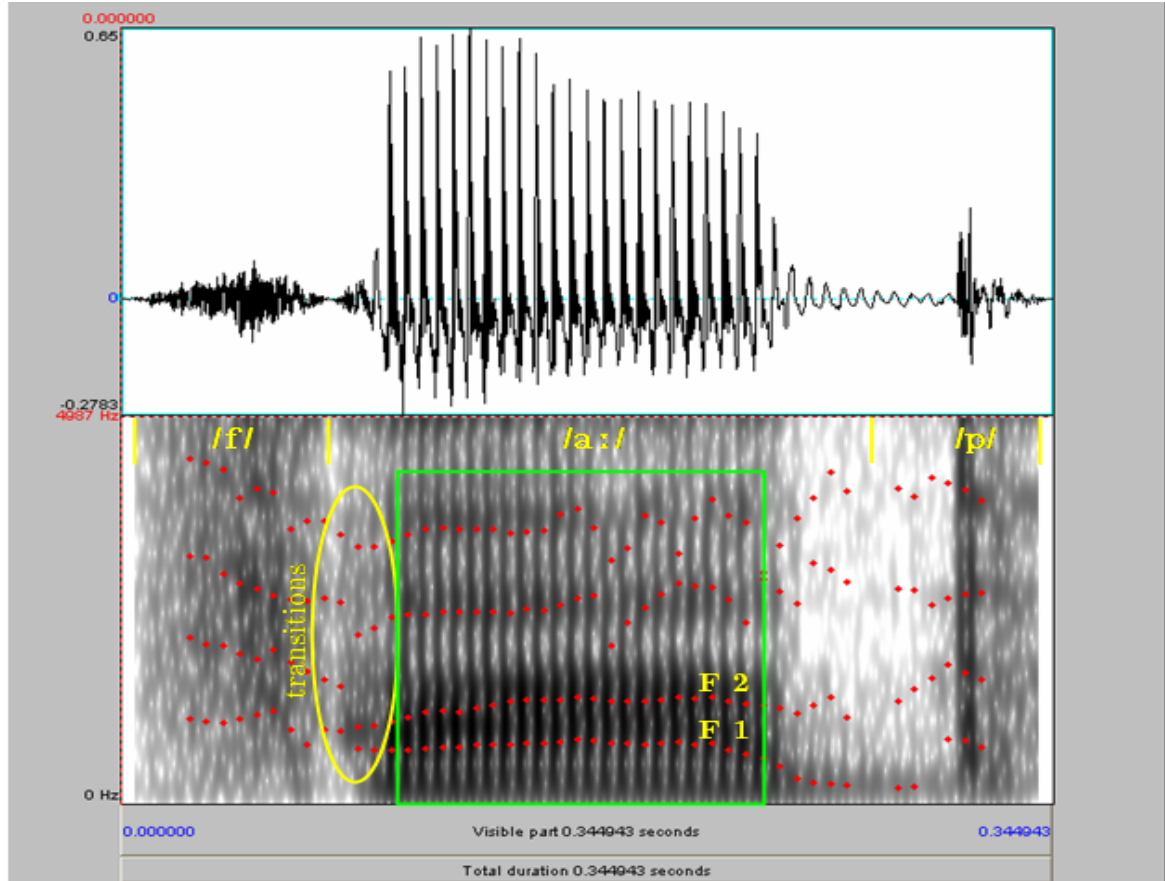


Figure 4: Oscillogram and spectrogram of the pseudo-word syllable “/fa:p/”.

The oscillogram is shown in the upper half, the spectrogram in the lower half of the figure. The green frame indicates the steady-state of the vowel /a:/, which was chosen for vowel length determination of this vowel.

Additionally, selected vowel parts were controlled acoustically to exclude possible co-articulations. Table 3 and figure 5 present the average durations of long and short vowels within the two pseudo-word syllables (i.e. /fVp/ & /nVp/; the single vowel durations within each pseudo-word syllable are given in Appendix D). What can be seen is that for short as well as for long vowels, vowel length increases with decreasing vowel height. Furthermore, the difference between the long and the short vowel of a pair also increases with decreasing vowel height. For each vowel pair, the long vowel was 66% to 89% longer than its short partner vowel.

Table 3: Average durations (msec) of long and short vowels produced in continuous speech syllables (/fVp/, /nVp/); grouped according to vowel height.

Vowel height	Vowel pair	Vowel duration (msec)		Difference (msec)
		long	short	long – short
high	/i:-ɪ/	91	51	40
	/y:-ʏ/	98	53	45
	/u:-ʊ/	102	57	45
mid	/e:-ɛ/	110	66	44
	/ø:-œ/	121	70	51
	/o:-ɔ/	128	75	53
low	/a:-a/	142	75	67

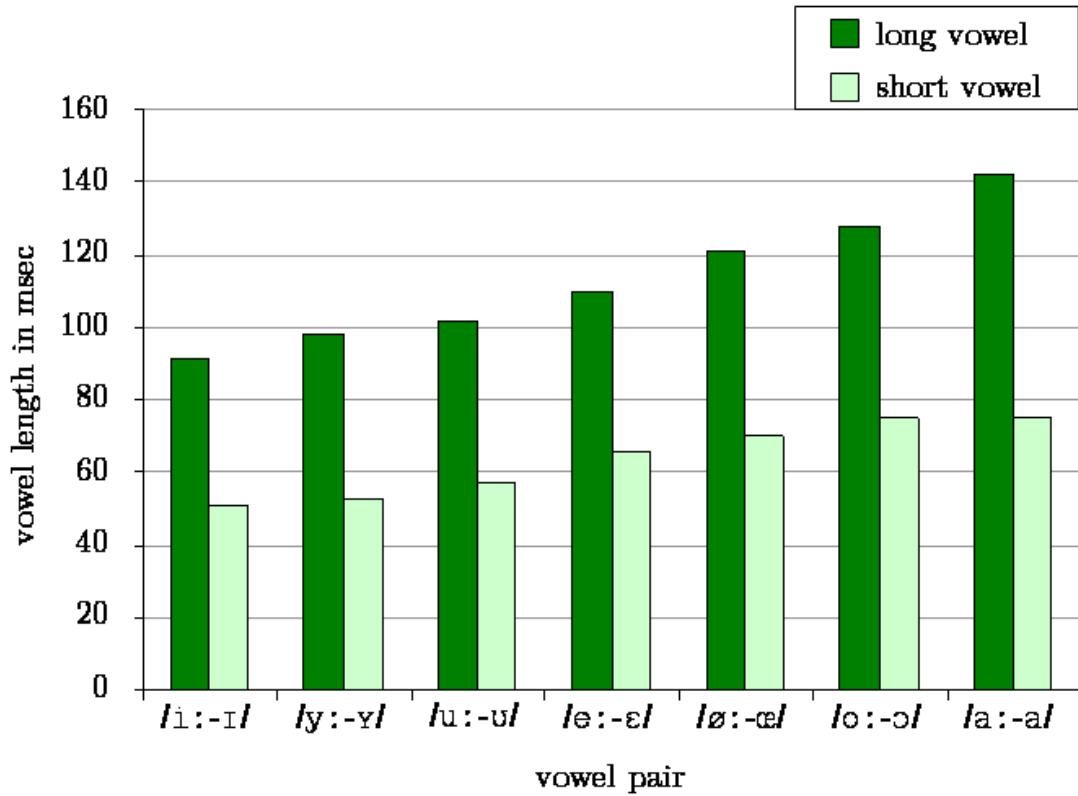


Figure 5: Average vowel lengths within the utilized stimuli (given in msec).

(2) On the basis of the determined vowel lengths, “Praat” (Boersma & Weenink, 2005) was used to accomplish the manipulations of the vowel lengths in two ways: In one condition, the duration of the short vowel of a pair was lengthened. This was done by adjusting its vowel length to the duration of its long original partner vowel, while spectral characteristics remained unchanged. For that purpose, a script was written in “Praat” (Boersma & Weenink, 2005) where the vowel lengths, the portions of the steady-state phase of the vowels and the factor, to which degree the vowels should be stretched, were defined. Based on that, the program performs linear interpolations within the selected portion and prolongs it to the defined duration. This resulted in a manipulated vowel with the length of a long original vowel but the spectral information of a short original vowel. In the following, we will refer to this manipulated vowel type as *lengthened short vowel*. In the other condition, the duration of the long original vowel was shortened by adjusting its vowel length to the duration of its short original counterpart, while spectral characteristics remained again unchanged. Here again, “Praat” (Boersma & Weenink, 2005) performs linear interpolations within the selected portion but now compresses it to the defined duration. This then resulted in a manipulated vowel with the length of a short original vowel but the spectral information of a long original vowel. In the following, we will refer to this manipulated vowel type as *shortened long vowel*.

To assure that the manipulated stimuli were not perceived as synthetic or unnatural, all participants were asked to indicate stimuli that sounded unnatural. All participants judged all stimuli as sounding perfectly normal, except one participant who rated one stimulus as sounding artificial.

2.1.3 Procedure: Vowel length discrimination paradigm

An auditory two-alternative, forced-choice discrimination experiment was conducted. In this *same-different* task, pairs of syllables were presented successively and participants had to decide whether they were the *same* or *different*. In the category *different*, the CVC-pairs only differed with respect to their vowel component, more specifically, to their vowel length. This resulted in the judgement of the following possible vowel combinations embedded in the two syllables as *different*: /i:-ɪ/, /y:-ʏ/, /u:-ʊ/, /e:-ɛ/, /ø:-œ/, /o:-ɔ/ and /a:-a/ in their natural condition. Examples of CVC-*different* pairs are /fa:p/ - /fap/ or /ni:p/ - /nɪp/.

There were three types of *different* trials: In the *phonological condition* an original long vowel was combined with its original short partner vowel. In these trials the vowel length difference was phonological in nature, i.e. vowels differed in spectral as well as temporal content. In the other two conditions, the vowel length difference was temporal in nature. In the *temporal spectrally long condition* (*temporal SL*) an original long vowel was paired with a shortened long vowel. That means that both vowels carried the spectral information of a long vowel, but differed exclusively with respect to duration. In the *temporal spectrally short condition* (*temporal SS*) an original short vowel was paired with a lengthened short vowel. In this condition, both vowels carried the spectral information of a short vowel but, again, differed exclusively with respect to duration.

In total, there were 42 *different* combinations: three types of difference (phonological vs. temporal SL vs. temporal SS), seven vowel types (/i:-ɪ/, /y:-ʏ/, /u:-ʊ/, /e:-ɛ/, /ø:-œ/, /o:-ɔ/ and /a:-a/), and two pseudo-word contexts (/fVp/ vs. /nVp/). Each combination was repeated four times, amounting to a total of 168 *different* trials used in the experiment. An equivalent number of *same*

trials were used to avoid response bias. For *same* trials, original as well as manipulated syllables with long and short vowels were used at an equal rate. Altogether, the experiment consisted of 336 trials, which were presented in pseudo-randomized order within four blocks of 84 trials. The division into four blocks was performed due to the length of the experiment and to control for decline of attention during the course of the experiment.

The experiment was performed individually in a sound-attenuated room. For stimulus delivery and experimental control, the software “Presentation” (Neurobehavioural Systems Inc., San Francisco, CA, USA) was used. The sound files were presented using a sound box (RME Hammerfall DSP System Multiface) controlled by a computer with a Centrino 1.6 GHz processor and a PCMCIA-card. Stimuli were presented via closed headphones (Beyerdynamic DT 770).

Participants were asked to decide whether two pseudo-word syllables presented in succession were the same or different. They were instructed to respond as quickly and as accurately as possible. Responses were given via button press using a separate response unit. The ISI between the two syllables of a pair was 250 msec. The inter-trial-interval was 2000 msec, starting with button press. Response latencies and accuracy were measured.

To familiarize participants with the task and the material, a practice phase was conducted prior to the experiment. The concept of vowel length was explained to the participants and clarified by means of real German words like *Stahl* (/ʃta:l/, [steel]) vs. *Stall* (/ʃtal/, [barn]), *Miete* (/mi:tə/, [rent]) vs. *Mitte* (/mitə/, [middle]), *Beet* (/be:t/, [‘vegetable’ patch]) vs. *Bett* (/bɛt/, [bed]) or *Höhle* (/hø:lə/, [cave]) vs. *Hölle* (/hœlə/, [hell]), *Fühler* (/fy:la/, [antenna]) vs. *Füller* (/fɥla/, [pen]), *Schrot* (/ʃʁo:t/, [pellet]) vs. *Schrott* (/ʃʁɔt/, [scrap]) or *Mus* (/mu:s/, [puree]) vs. *muss* (/mus/, [must]), etc. Then, a first set of practice

trials using real words with different vowel lengths was presented. A second set of practice trials introduced the type of pseudo-words used in the discrimination experiment. For that purpose, the CVC-syllable /pVm/, which was not part of the stimulus set of the experiment, was used. In all practice trials, participants received auditory feedback (tone) if their response was wrong. No feedback was given during the experiment. The whole experiment lasted about 45 to 60 minutes, including instruction (given in written and/or oral form; Appendix E) and practice session.

2.2 Statistical data analysis

Reaction times (RTs) were used to identify outliers and RTs of correct responses were used to control for a possible speed-accuracy trade off. Trials with a RT over 3000 msec were excluded from further analyses as outliers. As the focus of our study was on discrimination accuracy, further analyses on RTs were not performed. Error rates were analysed using repeated measures analyses of variance (ANOVAs). Post-hoc analyses were performed with follow-up ANOVAs, *t*-tests for independent samples and/or paired *t*-tests.

Same and *different* trials were analyzed separately (cf. Farell, 1985). *Same* trials were analyzed via two-factorial ANOVAs with the between-subject factor Group (dyslexics vs. controls) and the within-subject factor Stimulus type (original long vowel vs. original short vowel vs. manipulated long vowel vs. manipulated short vowel). *Different* trials were analyzed using three-factorial omnibus ANOVAs with the between-subject factor Group (dyslexics vs. controls) and the within-subject factors Type of difference (phonological vs. temporal SL vs. temporal SS) and Vowel type (/i:-ɪ/, /y:-ʏ/, /u:-ʊ/, /e:-ɛ/, /ø:-œ/, /o:-ɔ/ and /a:-a/).

Correlations between discrimination performance and spelling abilities were calculated with two tailed Pearson Correlation analyses.

2.3 Results

2.3.1 Speed-accuracy correlation

Pearson correlations between discrimination accuracy and RT were not significant. This was the case when both groups were analyzed together, $r = -.09$, $p = .57$, as well as when they were analyzed separately (dyslexics: $r = -.15$, $p = .52$; controls: $r = .02$, $p = .93$). Thus, there was no indication of a speed-accuracy trade off.

2.3.2 Discrimination accuracy

Responses on same trials: The two-factorial ANOVAs revealed no significant main effects and no interaction of response accuracy of *same* trials as measured in percentage correct, i.e., no Group effect (dyslexics: $M = 94.53\%$, $SD = 4.51\%$, controls: $M = 94.91\%$, $SD = 6.91\%$) nor Stimulus type effect was found ($M = 95.40\%$, $SD = 6.12\%$ for original long vowels; $M = 94.69\%$, $SD = 6.55\%$ for original short vowels; $M = 94.07\%$, $SD = 5.92\%$ for lengthened short vowels; $M = 94.73\%$, $SD = 7.28\%$ for shortened long vowels).

Responses on differing trials: The three-factorial ANOVAs revealed three main effects: Firstly, a main effect of Group, $F(1, 38) = 9.42$, $p < .01$, with dyslexics performing significantly worse ($M = 74.93\%$, $SD = 11.59\%$) than controls ($M = 84.81\%$, $SD = 8.54\%$). Secondly, a main effect of Type of difference, $F(2, 76) = 118.84$, $p < .001$, with pairwise comparisons revealing that performance in the phonological condition ($M = 97.95\%$, $SD = 2.38\%$) was significantly better than in the temporal SL condition ($M = 68.58\%$, $SD = 16.38\%$, $p < .001$) as well as in the temporal SS condition ($M = 73.01\%$, $SD = 17.54\%$, $p < .001$). Furthermore, performance was also better in the temporal SS condition than in the temporal SL condition ($p < .01$). Thirdly, a main effect of Vowel type, $F(6, 228) = 37.83$, $p < .001$.

.001, with declining mean values from low to high vowel pairs with $M = 94.35\%$ ($SD = 6.79\%$) for /a:-a/, $M = 83.84\%$ ($SD = 12.97\%$) for /o:-ɔ/, $M = 81.90\%$ ($SD = 13.48\%$) for /ø:-œ/, $M = 79.98\%$ ($SD = 16.07\%$) for /e:-ɛ/, $M = 76.46\%$ ($SD = 14.43\%$) for /u:-ʊ/, $M = 72.13\%$ ($SD = 13.86\%$) for /y:-ʏ/ to $M = 70.42\%$ ($SD = 15.54\%$) for /i:-ɪ/ was found. Pairwise comparisons showed that the low vowel pair /a:-a/ was discriminated better than all other vowel pairs ($p < .001$ for all t -tests) and that the highest vowel pair /i:-ɪ/ was discriminated worse than all others except /u:-ʊ/ and /y:-ʏ/ ($p < .001$, for all t -tests). From the remaining pairs the contrasts /e:-ɛ/ vs. /y:-ʏ/, /o:-ɔ/ vs. /u:-ʊ/, /o:-ɔ/ vs. /y:-ʏ/ and /ø:-œ/ vs. /y:-ʏ/ were also significant and showed decreasing performance with increasing vowel height ($p < .05$ for all t -tests).

Additionally, an interaction of Type of difference x Group, was found to be significant, $F(2, 76) = 8.56$, $p < .001$. The post-hoc test revealed that in the phonological condition, groups did not differ in accuracy (see Figure 6a), whereas in both the temporal SL and the temporal SS condition, controls showed a significantly higher response accuracy as compared to dyslexics, $t(38) = -3.42$, $p < .01$, and $t(38) = -2.74$, $p < .01$, respectively (see Figure 6b and 6c).

The interaction of Type of difference x Vowel type also reached significance, $F(12, 456) = 19.40$, $p < .001$. Post-hoc examinations showed that accuracy was better in the phonological than in the two temporal conditions for all vowel types ($p < .01$ for all paired t -tests) except /a:-a/. Here accuracy in the phonological condition was only superior compared to the temporal SL ($p < .05$) but not to the temporal SS condition. One-factorial post-hoc ANOVAs revealed that in the phonological condition, accuracy was equal for all vowel types (see Figure 6a). In the temporal SL and SS condition, however, accuracy depended on vowel type (see Figure 6b

and 6c). In the temporal SL condition, discrimination accuracy of the vowel pair /a:-a/ was better than that of all other vowel pairs ($p < .05$ for all paired t -tests). The accuracy of the /y:-ʏ/-pair was worse than that of all other vowel pairs ($p < .05$ for all paired t -tests), and accuracy of the /i:-ɪ/-pair was worse than that of /a:-a/-, /o:-ɔ/ and /ø:-œ/-pairs ($p < .05$ for all paired t -tests, respectively). In the temporal SS condition, the /a:-a/-pair again was more accurately discriminated than all other six vowel pairs ($p < .05$ for all paired t -tests), and the /o:-ɔ/-pair reached a higher accuracy than /u:-ʊ/, /y:-ʏ/ and /i:-ɪ/-pairs ($p < .05$ for all paired t -tests). Finally, the vowel pair /i:-ɪ/ was less accurately discriminated than all other vowel-pairs ($p < .05$ for all paired t -tests).

2.3.3 Correlation between discrimination accuracy and spelling abilities

Correlation analyses were performed separately for both groups. For control subjects a significant correlation between discrimination accuracy in general as well as discrimination accuracy on temporal trials and spelling abilities was found ($r = -.47$, $p < .05$; $r = -.45$, $p < .05$; respectively). Dyslexics showed a correlation between discrimination accuracy and spelling abilities on a 10%-level (general discrimination: $r = -.42$, $p = .06$; temporal discrimination: $r = -.41$, $p = .08$).

As the experimental task focuses on vowel length discrimination, additionally vowel length marking mistakes in the spelling test were counted and correlated with discrimination performance. In general the dyslexics' spelling abilities were highly related to their abilities in orthographic vowel length marking ($r = .61$, $p < .01$). However, there was no relation between discrimination performance (be it general or specific on temporal discrimination) and vowel length marking in the spelling test ($r = -.11$, $p = .66$).

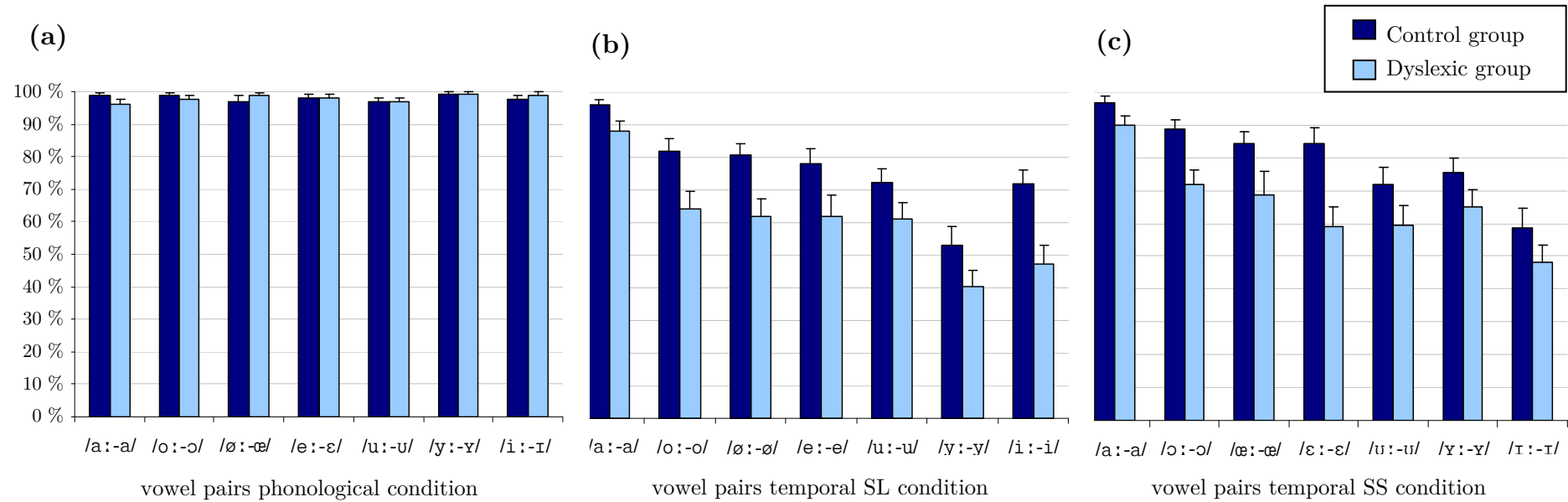


Figure 6: Percentage of correctly discriminated vowel pairs in *different* trials.

(a) Discrimination accuracy in the phonological condition (original long vowel paired with original short vowel; both vowels differ in spectral and temporal content); (b) Discrimination accuracy in the temporal SL condition (original long vowel paired with shortened long vowel; both vowels are spectrally long and differ only on the temporal dimension); (c) Discrimination accuracy in the temporal SS condition (original short vowel paired with lengthened short vowel; both vowels are spectrally short and differ only on the temporal dimension). Dark blue bars = control group; light blue bars = dyslexic group.

3. EXPERIMENT 2: fMRI EXPERIMENT⁶

3.1 Methods and Material

In the behavioural experiment a clear temporal processing deficit of the dyslexic sample could be observed. To now further scrutinize the neural correlates of the identified temporal auditory processing deficit the experiment was repeated half a year later under fMRI with the same sample and same paradigm.

3.1.1 Participants

The same sample as in the behavioural study (see section 2.1.1, pp. 24-25) participated in this study. Due to severe movement artefacts (which is explained in more detail in section 3.3.2, pp. 48-49) three dyslexics and four controls (all males) had to be excluded from this study. This resulted in 17 participants (12 males) with developmental dyslexia with a mean age of 18.6 years and 16 healthy control subjects (11 males) with a mean age of 18.7 years (for participant characteristics see table 4). Subjects were matched with respect to age, gender and intelligence. Informed consent was obtained in line with the Institutional Review Board of the University of Ulm. For further participant characteristics, diagnostic procedure and group inclusion criteria see section 2.1.1 (pp. 24-25).

As reading and spelling skills⁷ in this age as well as intelligence and handedness are not supposed to change within half a year no retesting was accomplished prior to the fMRI experiment.

⁶ Originally published in the journal “Brain and Language”#: Steinbrink C*, Groth K*, Lachmann T, Riecker A: Neural correlates of temporal auditory processing in developmental dyslexia during German vowel length discrimination: An fMRI study. *Brain and Language* 121: 1-11 (2012) [*first authors]. #All rights reserved by Elsevier.

⁷ None of the participants with dyslexia attended any reading or spelling course during the study.

Table 4: Participant group characteristics

	Dyslexics (n=17)		Controls (n=16)		<i>p</i> ^a
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
Age (years)	18.61	2.75	18.67	2.99	.954
Non-verbal IQ	115.50	13.67	119.78	9.79	.192
<i>Real-word reading</i>					
Errors (max. 48)	4.22	2.79	0.44	0.62	<.001
Reading time (sec.)	56.83	16.78	31.61	5.85	<.001
<i>Pseudo-word reading</i>					
Errors (max. 48)	11.28	6.09	3.17	1.92	<.001
Reading time (sec.)	109.78	40.61	65.83	14.62	<.001
<i>Spelling</i>					
Errors (max. 60)	39.44	8.99	12.17	6.97	<.001

Note. ^a *t*-test for independent samples.

3.1.2 Experimental Stimuli

The stimuli used here were a subset of the stimuli applied in the behavioural study. Based on the results of this preceding study and in order to assure enough repetitions as well as stable and strong hemodynamic responses, in the current fMRI experiment only three long-short vowel pairs within one CVC combination were chosen as experimental stimuli: The vowel pair with the highest vowel height, i.e. /i:-ɪ/, one vowel pair with mid vowel height, i.e. /e:-ɛ/ and the vowel pair with low vowel height, i.e. /a:-a/. These vowels were embedded in the CVC combination /fVp/, creating again monosyllabic pseudo-words. Like in the behavioural study these six syllables were used in its natural, inartificial way and are therefore referred as *original or natural vowels/stimuli*. For the second stimulus set this time only one type of manipulated stimuli was used. As results of

the behavioural experiment revealed no performance difference (see section 2.3.3, pp. 36-39) , neither for the control participants nor for the dyslexics, between the two temporally manipulated conditions and to avoid any confounding factors this time *only shortened long vowels* were chosen. To commemorate, this kind of vowels were generated by manipulating the lengths of the original long vowels. For that purpose (1) the vowel length of the natural vowels had to be determined (average vowel lengths of the long and short vowels used in this study are given in table 5). (2) the duration of each natural long vowel was then shortened and adjusted to the vowel length of the short partner vowel, while keeping the spectral characteristics of the long vowel constant. This resulted in a *shortened long vowel* with the length of a short vowel but the spectral information of a long vowel. For a more detailed explanation of stimulus generation and manipulation see section 2.1.2 (pp. 26-31).

Table 5: Average durations (in msec) of long and short vowels within the pseudo-word syllable /fVp/ produced in continuous speech.

vowel height	vowel pair	vowel duration		durational difference
		long vowel	short vowel	long-short vowel
high	/i:-ɪ/	91	52	39
mid	/e:-ɛ/	109	68	41
low	/a:-a/	140	75	65

3.1.3 Procedure: Vowel length discrimination paradigm under fMRI

The paradigm of this fMRI experiment was equivalent to the vowel length discrimination paradigm of the behavioural study explained in section 2.1.3 (pp. 32-34). That means the auditory two-alternative forced-choice discrimination task which was already applied in the behavioural study, was conducted and implemented in an event-related fMRI design. Within the scanner, participants listened to pairs of CVC-syllables which were either *same* or *different*.

In the category *same*, the two presented syllables were identical. In the category *different*, the paired syllables did only differ with respect to the vowel portion of the syllables, i.e. to vowel length. As only one kind of manipulated stimuli was utilized this time only two types of difference between long versus short vowels were varied: In the *phonological condition*, the vowel length difference was phonological in nature (i.e. vowels differed in spectral as well as temporal content) by combining a natural long vowel with its natural short complement. In the *temporal condition*, the vowel length difference was temporal in nature. Here a natural long vowel was always paired with the same but shortened long (i.e. temporally manipulated) vowel. That means that both vowels carried the same spectral information (that of a long vowel) and differed exclusively with respect to duration. In both experimental conditions (phonological vs. temporal) the selected three vowel pairs (/i:-ɪ/, /e:-ɛ/ and /a:-a/) were presented 20 times each. This amounted to a total of 120 *different* trials (2 conditions x 3 vowel pairs x 20 repetitions). To avoid response bias another 60 trials of stimulus pairs of the category *same* were interspersed into the experiment. For these *same* pairings, natural (phonological) as well as temporally manipulated stimuli with long and short vowels were used at an equal rate. Altogether, the whole experiment consisted of 180 trials (60 same, 120 different), which were presented in

pseudorandomized order within three blocks of 60 trials. Each of these blocks consisted of equivalent trial sets (20 same, 40 different).

The inter-stimulus-interval (ISI) between the two syllables of a pair was 250 msec. The inter-trial-interval (onset-to-onset) was based on the time of repetition (TR) of the scanning sequence and the decelerated hemodynamic response function. Furthermore, to improve the virtual sampling rate and thus the quality of the signal the onset of the stimulus pairs was jittered by interspersing gaps with onset-to-onset intervals of approximately 6 to 12 sec. A schematic representation of the experimental setup is given in figure 7.

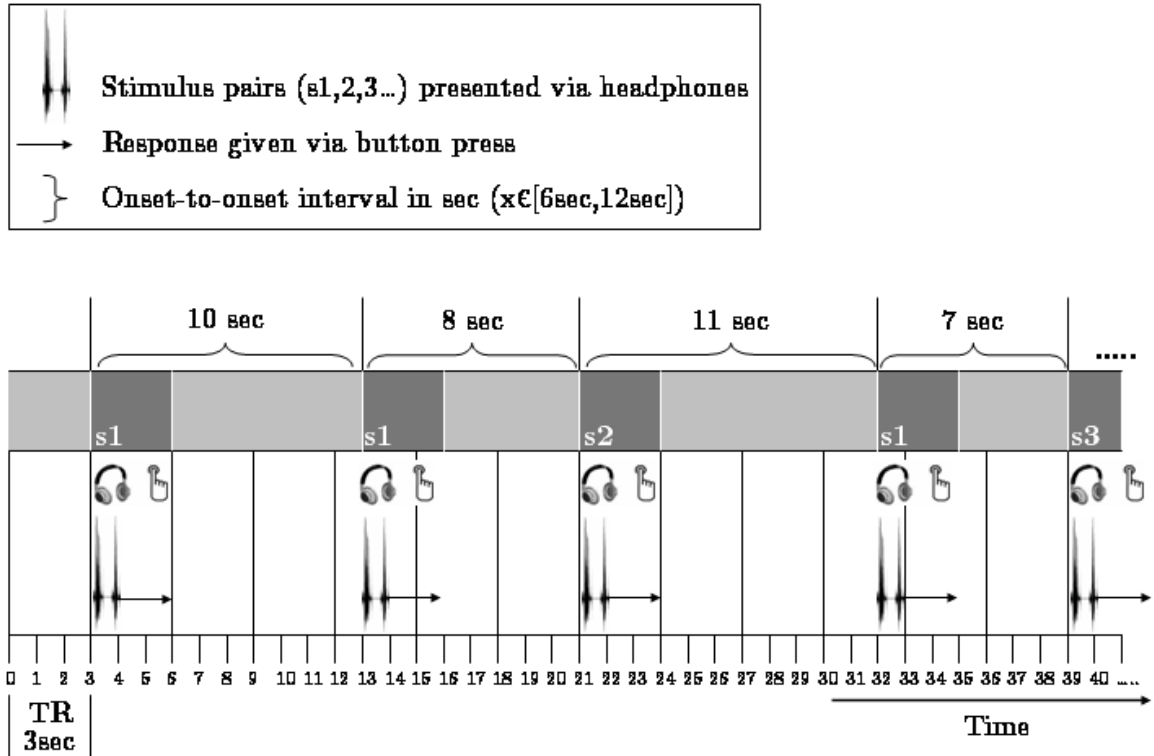


Figure 7. Schematic representation of the experimental setup.

Stimulus pairs (s1,2,3... = same or differing /fVp/ syllable pairs) were presented via headphones. Stimulus presentation was jittered by interspersing gaps. Responses were given via button press directly after stimulus delivery. The time course of scan acquisition is given in the lower half of the figure. Each (white) box represents the measurements across one complete brain volume comprising 32 slices (TR = 3 sec.). The onset-to-onset interval between stimulus trials varies between 6 and 12 sec due to the jittering effect between activation periods (marked dark grey) and scanning intervals (marked light grey).

For stimulus delivery and experimental control, again the software “Presentation” (Neurobehavioural Systems Inc., San Francisco, CA, USA) was used. Stimuli were presented via specially manufactured headphones for application within the fMRI scanner and were well discernible at a comfortable loudness level against the background noise of the scanner. The participants’ task was, like in the behavioural study, to decide whether the two pseudo-word syllables presented in succession were *same* or *different* with respect to vowel length. Participants were instructed to respond as accurately as possible. Again responses were detected by button presses (two alternatives: same vs. different) using an fMRI compatible response box.

Due to the participation in the behavioural experiment all subjects were already acquainted with the task. Still, they underwent a test run inside the scanner for practice purposes (with the practice syllable /mVk/), to get used to the scanner and the scanner noise as well as to determine the individual comfortable loudness level. For each subject, this individually adjusted value was kept constant across the whole experiment. Like in the behavioural experiment, in all practice trials, participants received auditory feedback (error tone) if their response was wrong. During the experiment, no feedback was given. The whole fMRI experiment (including training phase, functional measuring phase and anatomical scanning phase) lasted approximately 60 minutes.

3.2 fMRI data acquisition

Subjects rest on supine in a 3.0 T head-scanner (Magnetom Allegra, Siemens, Germany), their heads being secured by means of foam rubber in order to minimize movement artefacts. Thirty-two parallel axial slices, oriented along the AC-PC-line (AC = anterior commissure; PC = posterior commissure), with a thickness of 3.0 mm and a gap of 0.75 mm (25 %) were obtained across the entire brain volume using a gradient echo planar imaging sequence (64 x 64 matrix, field of view = 224 x 224 mm², echo time [TE] = 40 msec, repetition time [TR] = 3 sec, flip angle = 90°, voxel size = 3.5 x 3.5 x 3.0 mm, Bandwidth [BW] = 3004 Hz/Px). The experiment encompassed three scanning sessions comprising collectively 558 image volumes (3 runs x 186 images). Five initial dummy scans for the equilibration of T1 saturation effects and one final scan within each session were included. For anatomical localization of activated areas, the fMRI maps were superimposed on a T1-weighted three dimensional turbo-flash MPRAGE sequence (Magnetization Prepared Rapid Gradient Echo; BW = 130 Hz/Px, 208 sagittal slices, thickness = 1.0 mm, 256 x 256 matrix, field of view = 256 x 256 mm², flip angle = 12°; TE = 4.38 msec, TR = 2.2 msec).

3.3 Statistical data analysis

3.3.1 Analysis of behavioural data

The implementation of this fMRI experiment allowed parallel the measurement of hemodynamic brain activation also for acquisition of behavioural data. Response accuracy was analysed using repeated measures analyses of variance (ANOVAs). Post-hoc analyses were performed with follow-up ANOVAs, t-tests for independent samples and/or paired t-tests. More precisely, *different* trials were analyzed using a three-factorial omnibus ANOVA with the between-subject factor Group (dyslexics vs. controls) and the within-subject factors Stimulus condition (phonological vs. temporal) and Vowel type (/i:-ɪ/, /e:-ɛ/ and /a:-a/).

For both, fMRI as well as behavioural data analysis, *same* trials were treated as control condition. This was done under the assumption that performance for *same* trials should be near perfect within both groups, as same vowels are always matched in both their temporal and their spectral content, making the information relevant for decision redundant and thus the task easier (e.g., Lachmann & Geissler, 2002). This was also approved by the aforementioned behavioural study where very good performance for *same* trials was revealed with no group differences. Similarly, in this study performance on *same* trials was nearly perfect with no group effect, neither on the behavioural nor on the neural level. Therefore these trials were not further analyzed.

3.3.2 fMRI data analysis

Image pre-processing and statistical analyses were carried out using batch files of the Statistical Parametric Mapping software package SPM5 (Wellcome

Department of Cognitive Neurology, London, UK) and MATLAB 7.3 (MathWorks, Natick, MA). This statistical approach is based on the General Linear Model (GLM) and the Gaussian Field theory. Estimation of the GLM was performed after specification of the GLM design and matrix as well as after dedication of the fMRI data files and filtering parameters. For this, the standard procedure as suggested by SPM5 was used.

Overview: After data preprocessing for each individual, (1) single subject analyses using the hemodynamic response function with its first derivate was performed in order to determine the influence of vowel length discrimination in the phonological versus temporal condition in controls and dyslexics. (2) These data were used for the subsequent group analyses and (3) for subtraction analysis between controls and dyslexics.

Data preprocessing: fMRI data were first transformed to an ANALYZE-compatible format and corrected for slice timing differences and motion artefacts. Each anatomical T1-weighted image was realigned to the standard T1 template provided by the SPM5 software package. Coregistration of the functional images then relied on the same transformation matrix. Subsequently, spatial normalization and correction of MRI images into a standard echoplanar imaging (EPI) template in MNI standard space (standard space suggested by the Montreal Neurological Institute) was performed. Finally, the normalized data sets were smoothed with an isotropic Gaussian kernel (12 mm full-width at half maximum).

Movement artefacts: Head displacements during fMRI measurements influence spin excitation history and, thus, modify the BOLD signals of the respective scans. In order to account for these artefacts, the SPM5 software estimates the movement parameters during the realignment of functional images by comparing each slice to its reference, usually the first scan of a measurement series. As a second step of analysis, SPM5 performs a mathematical adjustment based on a moving average-

autoregression model of spin excitation history to remove persisting movement-related components (Frackowiak et al., 1997). It could be demonstrated that this procedure removes as much as 90 % of the variance due to movement-related effects in an fMRI time series. The present experiment measured continuously the complete brain volume using a TR of 3 sec. Head movement parameters were checked in all (x-, y- and z-) directions after the realignment step of signal analysis. Data sets with more than 2 mm motion in any direction were excluded from further analysis. As described before subjects performed a test run inside the scanner in order to get acquainted with the task and to adjust the loudness level but also to learn how to avoid strong/sudden head and associated jaw, lip, tongue and shoulder/arm movements. However, three dyslexics and four controls (all male) had to be excluded from this study due to movement artefacts.

Categorical hemodynamic response functions and subtraction analysis: At first, activation patterns obtained during the phonological and the temporal condition for dyslexics and controls were modelled. This provided the data base for all subsequent steps of statistical analysis. Contrast images (*different* trials minus rest) were calculated with one- and two-sample t-tests using SPM5 batch files. After single subject analyses second level group analyses were performed as whole-brain analyses. No specific region-of-interest (ROI) analyses were performed. To detect group differences subtraction analyses with t-tests for independent samples between controls and dyslexics (and vice versa) were performed for both the phonological and the temporal stimulus condition. For anatomical localization of activated areas, fMRI maps were superimposed on transverse sections of the structural MR images averaged across all subjects. The height threshold at voxel level was set at $p < .05$ (corrected for multiple comparisons).

Correlations analyses between discrimination performance and brain activation were performed with two tailed Pearson Correlations.

3.4 Results

3.4.1 Behavioural data – Discrimination accuracy for differing trials

The three-factorial ANOVA revealed three main effects: First, a main effect of Group, $F(1, 31) = 7.45$, $p < .05$, with dyslexics performing significantly inferior ($M = 83.21\%$, $SD = 11.78\%$) as compared to controls ($M = 92.08\%$, $SD = 5.71\%$). Second, a main effect of Stimulus condition, $F(1, 31) = 64.97$, $p < .001$, where performance in the phonological condition ($M = 98.51\%$, $SD = 3.39\%$) was better than in the temporal condition ($M = 76.49\%$, $SD = 18.38\%$). Third, a main effect of Vowel type, $F(2, 62) = 41.51$, $p < .001$. Pairwise comparisons showed that the low vowel pair /a:-a/ was discriminated significantly better ($M = 96.09\%$, $SD = 7.91\%$) than the other two vowel pairs (/i:-ɪ/: $M = 83.36\%$, $SD = 13.28\%$; /e:-ε/: $M = 83.07\%$, $SD = 12.82\%$; $p < .001$ for both t -tests).

Additionally, an interaction of Stimulus condition x Group, was found to be significant, $F(1, 31) = 5.95$, $p < .05$. Post-hoc analyses revealed that in the phonological condition, groups did not differ in accuracy, whereas in the temporal condition, controls showed a significantly higher response accuracy ($M = 84.47\%$, $SD = 11.47\%$) as compared to dyslexic participants ($M = 68.98\%$, $SD = 20.70\%$), $t(31) = -2.64$, $p < .05$ (see figure 8).

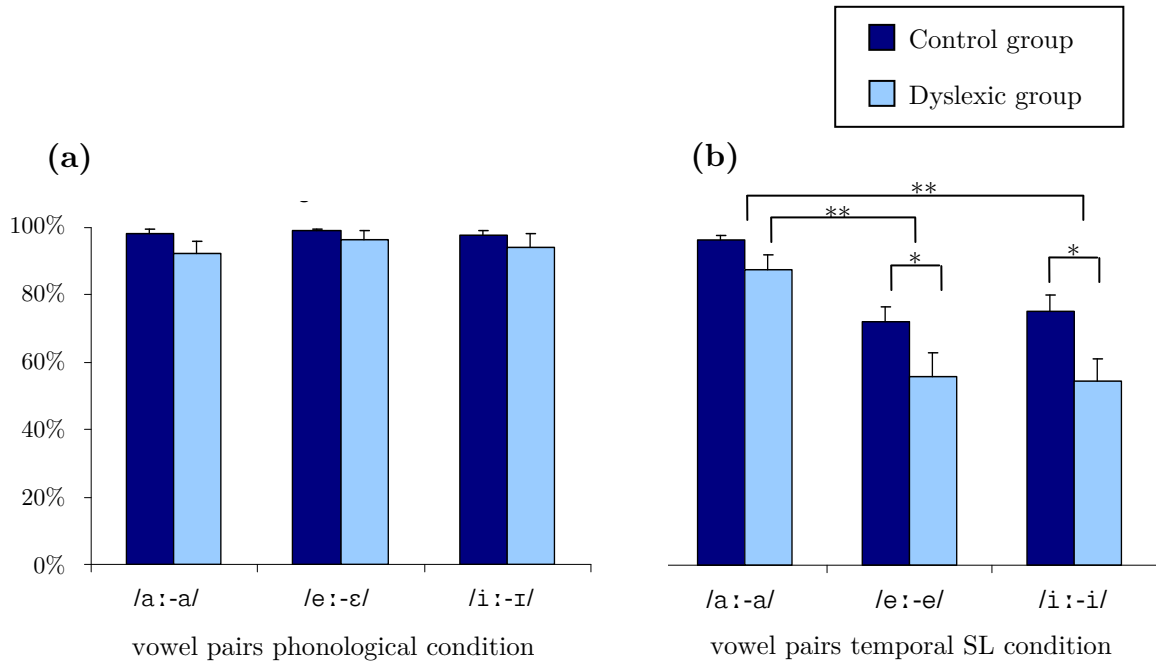


Figure 8. Discrimination accuracy for *different* trials given in percent correct.

(a) Performance during the phonological condition (original long vowel paired with original short vowel; both vowels differ in spectral and temporal content); (b) Performance during the temporal condition (original long vowel paired with shortened long vowel; both vowels are spectrally long and differ only on the temporal dimension). Significance of differences: * = $p < .05$; ** = $p < .01$; dark blue bars = control group; light blue bar = dyslexic group.

3.4.2 fMRI data – task specific BOLD response to trials of the category *different*

On the basis of the computation of the categorical hemodynamic response functions the auditory cortex, the insula and the inferior frontal gyrus (IFG) of both hemispheres were defined as task specific regions on which all subsequent statistical data analyses were performed. Brain activation during different trials was compared to brain activation during rest. Initially, fMRI data analysis of different trials was performed according to the behavioural data analysis focusing on Group, Stimulus condition and Vowel type effects. As hemodynamic brain activation for the three different vowel types (high vs. mid vs. low) did not differ,

they were taken together for further analyses. Hence, stimuli were analyzed only with respect to stimulus condition (phonological vs. temporal) and group (dyslexics vs. controls), thus concentrating on the effect of temporal information processing for vowel length discrimination.

Stimulus condition calculations revealed different neural responses within the above defined regions. During discrimination of phonological items (i.e. when activations in *different* trials in the phonological condition were contrasted with rest), only brain activation within the bilateral auditory cortex (superior temporal gyrus [STG]) could be observed (figure 9, top). Analysis of temporal trials (i.e. when activations in *different* trials in the temporal condition were contrasted with rest), showed an additional task specific bilateral activation of the insular cortex in both groups (figure 9, bottom). Furthermore, during this condition controls demonstrated a significant activation within the left inferior frontal gyrus (figure 9, bottom right). The values of all significant activation maxima (T values) and the SPM coordinates, taken from the SPM anatomy toolbox (http://www.fz-juelich.de/inb/inb-3//spm_anatomy_toolbox), of the identified task specific brain regions are given in table 6.

To detect group differences subtraction analyses between controls and dyslexics (and vice versa) in the temporal condition were performed, demonstrating no significant effects. The subtraction analyses showed, however, tendencies for higher activations in the left anterior insula ($T = 3.06$, $p = .066$) and the left IFG ($T = 3.02$, $p = .078$). Thus, the lack of group differences in the subtraction analyses might be due to lack of statistical power.

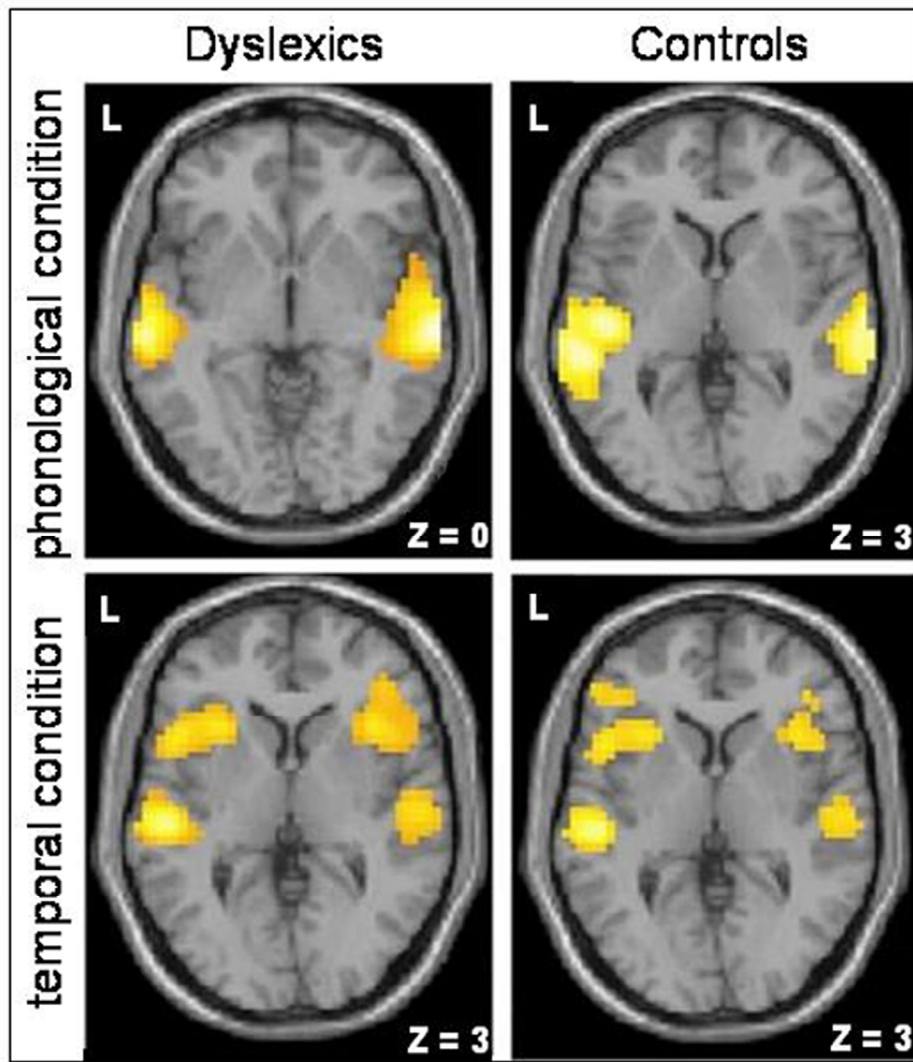


Figure 9: Hemodynamic brain activation during *different* trials.

During the phonological condition (top) bilateral activation of the auditory cortex in dyslexics (left) and controls (right) is found; During the temporal condition (bottom) additional bilateral activation of the insular cortex in dyslexics (left) and controls (right) and in the left IFG in controls (right) can be observed.

Note. Brain activation is displayed on transverse section of the anatomical reference images (SPM5 template); left hemisphere (L) is shown left and right hemisphere is shown right; Z = distance to inter-commissural plane. Brain regions were determined using the SPM anatomy toolbox (http://www.fz-juelich.de/inb/inb-3//spm_anatomy_toolbox) and aal (anatomical automatic labeling) toolbox (<http://www.cyceron.fr/freeware>).

Figure taken from original publication: Steinbrink C, Groth K, Lachmann T, Riecker A: Neural correlates of temporal auditory processing in developmental dyslexia during German vowel length discrimination: An fMRI study. *Brain and Language* 121: 1-11 (2012); All rights preserved; with kind permission from Elsevier.

Table 6: Categorical analysis during discrimination of vowels pairs in the phonological and temporal condition in control subjects and dyslexic participants.

		Phonological condition		Temporal condition	
		Dyslexics	Controls	Dyslexics	Controls
Inferior Frontal Gyrus (BA 44/45)	left	n.s.	n.s.	n.s.	T = 4.02 [-45 36 0]
Anterior Insula	left	n.s.	n.s.	T = 4.09 [-36 18 3]	T = 3.84 [-36 15 3]
	right	n.s.	n.s.	T = 4.23 [42 18 3]	T = 4.54 [36 18 3]
Superior Temporal Gyrus (BA 40 /41)	left	T = 3.50 [-51 -18 0]	T = 4.24 [-51 -21 3]	T = 4.58 [-48 -21 0]	T = 3.74 [-48 -21 3]
	right	T = 4.39 [54 -21 3]	T = 6.16 [54 -18 3]	T = 4.89 [54 -21 0]	T = 4.91 [51 -21 3]

Notes: T values represent activation maxima within each region. SPM-coordinates are given in square brackets. BA = Brodmann Area; n.s. = not significant. Brain regions were determined using the SPM anatomy toolbox (http://www.fz-juelich.de/inb/inb-3/spm_anatomy_toolbox) and aal (anatomical automatic labeling) toolbox (<http://www.cyceron.fr/freeware>).

Therefore, additional subgroup analyses were performed based on high and low discrimination performance in the temporal task. This allowed for comparing the hemodynamic brain activation in the temporal condition in these subgroups irrespective if subjects were classified as controls or dyslexics. In high performers, more than 90% of responses were correct ($n = 6$; 5 controls and 1 dyslexic), while in low performers less than 60% of responses were correct ($n = 5$ dyslexics). This analysis revealed decreased hemodynamic brain activation of the anterior insular cortices (left: $T = 3.92$, $p = .037$; right: $T = 5.97$, $p = .008$) and the left IFG ($T = 5.47$, $p = .02$) in low compared to high performing participants (see figure 10).

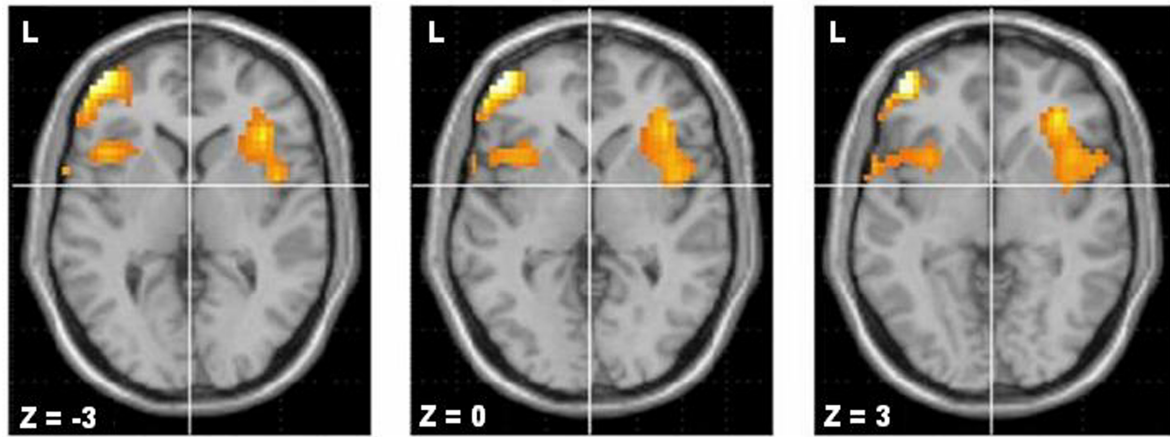


Figure 10. Subgroup subtraction analysis (high vs. low performers).

Participants with high discrimination accuracy on different trials during the temporal condition show increased brain activation as compared to participants with low discrimination accuracy in the following brain regions (given with T-values and [SPM-coordinates]): 1. left anterior insula: 3.92 [-35 21 -3]; 2. right anterior insula: 5.97 [42 15 -3]; 3. left IFG: 5.47 [-45 48 -3].

Note. Brain activation is displayed on transverse section of the anatomical reference images (SPM5 template); left hemisphere (L) is shown left and right hemisphere is shown right; Z, distance to inter-commissural plane. Brain regions were determined using the SPM anatomy toolbox (http://www.fz-juelich.de/inb/inb-3//spm_anatomy_toolbox) and aal (anatomical automatic labeling) toolbox (<http://www.cyceron.fr/freeware>).

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3.4.3 Correlation between discrimination performance and brain activity

Calculations on correlations between measures of behavioural discrimination performance and measures of brain activity revealed significant effects on a 10%-level only. When analyzing groups separately trends for significant correlations in the dyslexic group between discrimination performance in the temporal condition and activation of the left insula ($r = .46$, $p = .08$) as well as the left IFG ($r = .42$, $p = .09$) were found. Furthermore, like in the behavioural study, spelling abilities and discrimination performance correlated significantly in the dyslexic sample (phonological condition: $r = -.51$, $p < .05$; temporal condition: $r = -.62$, $p < .01$).

4. DISCUSSION

4.1 Discussion of the Behavioural Experiment

The aim of this first study was to investigate phonological versus temporal aspects of vowel length processing in developmental dyslexia on a behavioural level. In an auditory *two-alternative forced-choice discrimination* experiment, pairs of German vowels, each embedded into monosyllabic pseudo-words were compared and had to be judged on the basis of their vowel lengths as *same* or *different*. The accuracy of vowel length discrimination was analyzed. The discrimination of vowel lengths is a phonological task, as vowel length is phonemic in German. Long and short German vowel pairs differ with respect to both their temporal (quantity) and spectral (quality) content. Therefore three types of difference were used here. In the phonological condition, both temporal and spectral information was available for discrimination. In the two temporal conditions (temporal spectrally long and temporal spectrally short), spectral information was kept constant between the two vowels of a pair, thus the two vowels within the syllables differed only with respect to their temporal content. The results revealed a temporal processing deficit for the dyslexic sample. When the participants had to decide solely on the basis of durational cues, dyslexics performed significantly inferior compared to controls. Furthermore a correlation between discrimination accuracy and degree of impairment corroborates this finding.

4.1.1 German vowel length discrimination in general

Discrimination of same trials: Both control and dyslexic groups had no problems with the judgement on *same* trials, no matter whether the two syllables contained

original, manipulated, long or short vowels. This was expected as vowels within *same* trials were always matched in both their temporal and their spectral content, making the information relevant for decision redundant and thus the task easier (e.g., Lachmann and Geissler, 2002). This also explains the missing group effect. A possible temporal information processing deficit is expected to lead to incorrect *same* responses during *different* trials but not vice versa.

Discrimination of differing trials: Concerning *different* trials, both groups performed better in the phonological condition than in the temporal conditions. This was expected because in the phonological condition, as in the *same* trials, spectral and temporal information call jointly for the response category required. The groups performed equally across vowel types. In the phonological condition, discrimination accuracy was the same for all seven vowel pairs. As a result, one can conclude that when both temporal and spectral information (quantity and quality) are available, the vowel type does not matter. In the temporal conditions, response accuracy generally got worse. This indicates that spectral information is an important cue for vowel length discrimination. Most importantly, in the temporal conditions, accuracy changed with vowel type. The high vowel pair /i:/ - /ɪ/ had a lower accuracy than most other vowel pairs and the low vowel pair /a:/ - /a/ had a higher accuracy than all other six vowel pairs. In other words, accuracy degraded from the low (/a:/ - /a/) to the high vowel pair (/i:/ - /ɪ/), which is in line with the findings from vowel length *identification* experiments (Weiss, 1974; Sendlmeier, 1981; Strange and Bohn, 1998).

That means, for the discrimination of low vowels, temporal information (quantity) is more relevant than spectral one, whereas for the discrimination of high vowels spectral information (quality) has a higher relevance. How can this be explained?

The high vowels /i:/ and /ɪ/ differ only slightly on the temporal dimension but show large spectral differences, which make them sound different. In contrast, the low vowels /a:/ and /a/ are very similar with respect to their spectral characteristics (Sendlmeier, 1981; Strange and Bohn, 1998; Weiss, 1974), but show larger temporal differences than the other vowel pairs. This explains why, in low vowels, vowel length discrimination is predominantly accomplished by temporal cues. Weiss (1974) has stated that quantity becomes the more important as a cue for vowel length perception, the closer the long and short vowel of a pair are in quality. Thus, it seems that the acoustic cue with the higher saliency is predominantly utilized for vowel length discrimination in a particular vowel pair.

4.1.2 Vowel length discrimination in dyslexics compared to controls

Phonological condition: There was no group effect found in the phonological condition. When temporal, as well as spectral information was available for vowel length discrimination, as is the case in natural German language, accuracy was equivalent in dyslexics and controls. Thus, dyslexic adolescents and adults are not impaired in phonological vowel length processing. This result contradicts the finding by Landerl (2003), who investigated vowel length identification in German-speaking children with poor spelling abilities and found these children to perform less accurately than controls. Furthermore, these results also do not corroborate those of Lieberman and colleagues (1985), who found deficits in dyslexic adults when performing English vowel identification. These contrasting results can either be explained by methodological differences or maybe by age effects. Concerning methodological differences most importantly *discrimination* of vowel length is accomplished via direct comparison of the two stimuli presented and does not rely on access to long-term phonological representations. Vowel length *identification*,

on the contrary, requires matching the perceived vowel with its long-term representation. Thus, deficits in accessing long-term phonological representations (Ramus and Szenkovits, 2008) or underspecifications of long-term phonological representations (Boada and Pennington, 2006; Elbro and Jensen, 2005; Swan and Goswami, 1997a, b) might have lead to the observed deficits in the identification studies. On the other hand, the age of the participants might play a crucial role. One could hypothesize that children have more difficulties on vowel length discrimination than adolescents and adults, as their linguistic system is not yet completely developed. Maybe adolescents get more acquainted with this task with age or learn to compensate this deficit, why no group differences on the phonological condition can be observed. Probably such a temporal auditory processing deficit is more pronounced in children and thus leading also to phonological impairments, which are described as the core symptoms in dyslexia. To clarify this, a replication of this experiment with children might be necessary.

Temporal condition: In both temporal conditions, when only temporal information was available for vowel length discrimination, dyslexics performed less accurately than controls. This finding can be interpreted as evidence for a temporal auditory processing deficit in dyslexia. The explanation might be that auditory temporal processing is impaired in dyslexics, thus leading to increased error rates when vowel length discrimination is based only on temporal information.

As expected, there was a correlation between discrimination accuracy in the temporal conditions and general spelling abilities of the dyslexic sample, which might indicate that temporal processing difficulties indeed influence spelling abilities. But in the same time no relation between vowel length marking abilities and discrimination performance were found. This however, might be due to the relatively small range of error rates in vowel length marking in the spelling test.

In this experiment the temporal difference between the long and short vowel of a pair increased from 40 ms for the high vowel pair /i:/ - /ɪ/ to 67 ms for the low vowel pair /a:/ - /a/. Assuming a temporal processing deficit to be responsible for the group effect in discrimination accuracy, one might expect these effects to increase with decreasing temporal differences between the two vowels of a pair. This was not completely found. On the one hand, the results show that there is clear deterioration in performance with decreasing durational vowel pair difference. On the other hand, the discrimination accuracy of *both* groups deteriorated with decreasing durational vowel pair differences. Still, dyslexics performed worse than controls on all vowel pairs.

The obtained temporal processing deficit in dyslexia of this study was found using a *same-different* design. Banai and Ahissar (2006) argued that the sensitivity of an experimental design to auditory processing impairments depends mainly on task complexity rather than on material and that this fact might explain the contradicting results in the field. In their study they used the same material, but varied the task demand for auditory processing from rather simple tasks, such as identification and *same-different* comparison, to more difficult ones requiring parametric comparisons or judging the ordinal position of a repeated stimulus. They found group effects for the latter set of tasks only, independent of stimulus material (tones vs. speech sounds). The design used in this work can therefore be attributed as being a “simple *same-different* discrimination” task. Still, clear group differences could be observed, and their appearance depended on the stimulus manipulation. This shows that using experimental manipulations of acoustic cues inherent in speech stimuli, auditory processing deficits can be revealed also via rather simple experimental paradigms.

The advantage of simple designs is that confounding factors such as attentional or short-term memory limitations can be minimized. Nevertheless, these factors also have to be taken into account (Ahissar et al., 2006). For this study, however, one can rule out memory impairments as an explanatory factor for the group effects, because the phonological and temporal processing conditions were equivalent in task complexity and dyslexics were impaired in one condition only. Attentional differences should also be considered (Rüsseler et al., 2002), as the temporal conditions can be viewed as somewhat more demanding than the phonological one. Therefore the experiment was split into four equivalent blocks and performance was analyzed as a function of the experimental block, for both groups. Still, accuracy remained the same within both groups across the course of all four experimental blocks, as shown in Appendix F.

In the temporal conditions of the present study, a natural speech sound is always combined with a manipulated one. Blomert and Mitterer (2004) used a categorical perception task in which synthetic sounds ranged perceptually from /ba/ to /da/, and “naturally sounding speech” ranged from /ta/ to /ka/. Group differences were only found for the former set of stimuli. The authors (2004) argued that group differences found in the processing of synthetic speech sounds between dyslexics and controls can not be generalized to the processing of natural speech sounds. Thus, the difference between the phonological and temporal conditions used here could be attributed to the difference in naturalness. However, none of the vowels in any condition were produced synthetically in the present study. They were generated by manipulating the natural vowels using a special computer software and therefore correspond to the “natural sounding speech sounds” as suggested by Blomert and Mitterer (2004). These vowels subjectively sounded as natural as the original ones, which was double checked by a naïve independent sample of lab

workers. Furthermore, after the task participants were asked if stimuli sounded unnatural, which was negated by almost all subjects. Moreover, other studies (e.g., Lachmann et al., 2005) used the natural syllables /ba/ and /da/ in different designs and found impairments in dyslexic participants. Thus, it seems that dyslexics' deficits in the processing of speech are not principally confined to synthetic stimuli.

One may conclude that neither task nor stimulus restrictions alone can explain the findings of auditory processing deficits in dyslexia or the lack thereof. It seems rather that the interaction between task and stimulus determines the sensitivity of the experimental design to the detection of auditory impairments. Thus, none of the aforementioned studies can deny the interpretation of results obtained here in terms of a temporal processing deficit in dyslexia.

4.2 Discussion of the fMRI experiment

The aim of the fMRI study was to investigate the neural correlates of the observed auditory temporal processing deficit found in the dyslexic sample of the preceding behavioural study. The same task and stimuli were used and repeated with the same group of participants under fMRI. In a *same-different* task pairs of German vowels differing in vowel length, each embedded into monosyllabic pseudo-words, were compared. This time the accuracy of vowel length discrimination as well as the task specific hemodynamic brain activation were analyzed. To recall, long and short German vowels differ with respect to both their temporal (quantity) and spectral (quality) content. Based on that, two experimental conditions were compared: In the phonological condition, both temporal and spectral information was available for discrimination. In contrast, in the temporal condition, spectral information was kept constant between the two vowels, thus the vowels within the syllable-pairs differed only temporally.

Most former imaging studies preferentially utilized passive listening paradigms to investigate that topic. Participants of this experiment however, had to make explicit judgements concerning phonological versus temporal vowel length differences. This allows for a direct comparison of the participants' performance and the corresponding task specific neural activation.

The behavioural results of this fMRI study replicate the results of the previous experiment. Based on the discrimination performance for *different* trials, the behavioural findings obtained in the fMRI experiment again suggest a temporal auditory processing deficit in dyslexic individuals: In the phonological condition, when both spectral as well as temporal information was available for decision making (as is the case in natural German language), accuracy was equivalent in

dyslexics and controls. However, when only temporal information was available for vowel length discrimination, dyslexics performed on all vowel types less accurately than controls and showed decreasing performance with increasing vowel height.

On the neural level during the phonological condition, hemodynamic brain activation was observed bilaterally within the auditory cortices (STG) in controls and dyslexics with no group differences. Analysis of the temporal condition revealed an additional bilateral activation of the anterior insular cortices in both groups and a significant activation within the left IFG in controls. Group subtraction analyses did however not demonstrate significant effects, although there was a tendency ($p < 0.1$) of increased hemodynamic activation in the left anterior insula and left IFG. Likewise, in the correlation analysis of the dyslexic sample there was also a tendency ($p < .01$) for a positive correlation between discrimination accuracy during the temporal condition and brain activation of the left insula and left IFG. Therefore a subgroup subtraction analysis was performed. It was based on performance in the temporal condition (high performers with over 90% correct responses [$n = 6$; 5 controls and 1 dyslexic] were compared to low performers with less than 60% correct responses [$n = 5$; only dyslexics]) and showed significantly decreased hemodynamic activation of the anterior insular cortices and the left IFG in low- compared to high-performing subjects.

4.2.1 Neural correlates of temporal auditory processing of vowel length in control subjects

Generally, studies in healthy control subjects demonstrate functional hemispheric asymmetry during analyzing speech. The left hemisphere is supposed to process information in shorter temporal integration windows (25-50 msec; e.g., Ackermann et al., 2001; Ackermann and Riecker, 2004; Riecker et al., 2008; Hickok and Poeppel, 2000, 2004; Ivry and Robertson, 1998; Poeppel, 2001; Zatorre et al.,

2002), providing higher temporal resolution at the expense of lower spectral resolution. Vice versa the right hemisphere is proposed to preferentially process information over longer time windows (150-250 msec; Jamison et al., 2006; Poeppel, 2001; Schönwiesner et al., 2005; Zatorre and Belin, 2001), at least for non-speech stimuli. This is further supported by a current study by Abrams and colleagues (2008), who found that slow temporal features in speech (like the speech envelope) are preferentially processed by the right hemisphere. In consequence, hemispheric differences might reflect a higher specialization of the left hemisphere concerning rapid temporal processing, and of the right hemisphere for fine and subtle extraction of the spectral information of the (speech) signal.

In contrast to these studies, this work shows such a lateralization effect during the temporal condition only at the level of the left IFG. During the phonological discrimination task specific hemodynamic brain activation was observed bilaterally, in the left and right auditory cortex. When focusing on the hemodynamic brain activation specific to the processing of temporal stimuli again bilateral activation of the auditory cortex (STG) was present. This is on the one hand, in accordance with other studies, like for example by Zaehle and collaborators (2004) who found primary and secondary auditory cortex activation during perception of rapid temporal information, independent of the linguistic demands. They investigated rapid temporal information processing by means of a gap detection and syllable discrimination task with a sparse sampling paradigm. On the other hand, in their study an exclusively left-sided task specific activation was reported, which was not found here. This might be due to the differing acquisition paradigm. Continuous scanning (as performed in this study in contrast to sparse sampling which was used by Zaehle et al., 2004), with its permanent acoustic scanner noise might of course interfere with the auditory stimuli, so that

fine-graded hemodynamic signal changes are not detected. However, there are also several other neuroimaging studies who compared slow and fast spectral changes but failed to show a lateralization effect (Hall et al., 2003; Temple et al., 2000) on the level of the auditory cortex. It is more probable that such an asymmetry is restricted to brain regions being specifically involved in temporal auditory processing.

Additionally to the activation of the auditory cortices, a clear bilateral activation of the anterior insular cortices was revealed for both groups during the temporal condition. The insular cortex as an important neural substrate for processing rapid temporal aspects of non-speech as well as speech stimuli has already been suggested by former studies (Steinbrink et al., 2009; Ackermann et al., 2001; for review, see Bamiou et al., Luxon, 2003). Especially the *anterior* insula, which was also found in this study, was identified as part of a frontostriatal timing circuit, (Kosillo and Smith, 2010). The exact role of the anterior insula in timing, however, remains uncertain (for review, see Kosillo and Smith, 2010). Quite some studies suggest a lateralization effect within this region to the left hemisphere during temporal processing (Tervaniemi and Hugdahl, 2003; Ivry and Robertson, 1998; Hickok and Poeppel, 2000, 2004; Zatorre et al., 2002; Ackermann et al., 2001; Ackermann and Riecker, 2004; Riecker et al., 2008). Still, this could not be replicated in this study. Probably, the duration differences between long and short vowels used here were not adequate in order to elicit a strong lateralization effect as reported in other papers. In the present study the absolute durational differences between long and short vowels of a pair ranged from 39 to 65 msec (see table 5). Poeppel (2001) proposes that speech signal information within a short temporal integration window of 25-50 msec is preferentially extracted by left hemisphere mechanisms. In accordance to that, Belin and colleagues (1998) used in their study stimuli with either rapid formant transitions of 40 msec (in the range

of Poeppels' proposed time window) or slow transitions of 200 msec. They too, found a clear left-biased asymmetry for the processing of rapid frequency transitions. However, when parametrically analyzing the hemodynamic brain activation specific to the three different vowel types used in this fMRI experiment (high vowel pair /i:/ - /ɪ/ with a durational difference of 39 msec, mid vowel pair /e:/ - /ɛ/ with a durational difference of 41 msec and low vowel pair /a:/ - /a/ with a durational difference of 65 msec) no differing activation pattern and no left-sided asymmetry could be observed between the first two vowel types, which duration differences lie in the short temporal integration window proposed by Poeppel (2001), and the low vowel type with a longer time range. Maybe the duration differences between the utilized vowel types were not large enough (i.e. only 2 msec between the high and the mid vowel pair and 24 msec between the mid and low vowel pair) or the duration difference of the low vowel pair /a:/ - /a/ with 65 msec was still too short to elicit a strong lateralization effect. Therefore, the question remains why a lateralization effect could not be observed on this level.

Another reason for the lacking left-sided asymmetry on this brain level might be that the hemodynamic activation during the highly cognitive task of this study overlays the subtle activation differences for rapid and slow temporal processing. Maybe a passive listening paradigm would have been more appropriate to reveal such subtle differences and lateralization effects as reported by others. However, not all previous studies report a clear lateralization effect. Gandour et al. (2002) investigated vowel length discrimination for Thai vowels in an fMRI experiment and found bilateral activation of the insular cortex. Similarly, Kosillo and Smith (2010) summarize that the issue of hemispheric lateralization in time perception, either in the insula or more generally, remains unsolved.

In addition to the bilateral activation of the insula the temporal stimulus condition elicited a supplementary activation of the left IFG in control subjects. Only now, at the level of the IFG a clear lateralization effect is existent. This is in accordance with previous studies who describe the left IFG as an important neural region within a network for processing rapid temporal cues (Joanisse and Gati, 2003; Tervaniemi and Hugdahl, 2003) in speech and non-speech stimuli. Gandour and colleagues (2002), for example, also report in their vowel length discrimination task activation of left prefrontal areas like the left IFG, irrespective if vowel length differences were long or short. They suggest that in left prefrontal regions, like the IFG, segmental as well as suprasegmental duration features are processed. In a parametric passive listening paradigm, with speech and non-speech stimuli presented at six different frequency rates (1-9 Hz), Steinbrink and colleagues (2009) tested rate-dependent auditory processing capabilities in controls and dyslexics. They too, found a significant hemodynamic activation of the left IFG in response to speech and non-speech stimuli.

Another explanatory factor for the additional activation of the left IFG during the temporal condition might be task difficulty as argued by Poldrack and colleagues (2001). In their experiment participants had to perform an auditory sentence verification task on speech samples that were temporally compressed to different degrees. The results suggest that left IFG activation might tend to increase as a function of any manipulation which leads to increased processing demands. This might also apply to this experiment. The discrimination of vowel length in the phonological condition is somehow easier as both spectral as well as temporal information is available for decision making. In contrast to that, during the temporal condition participants have to rely solely on the temporal information as it is the only distinguishing factor between the two given vowels, thus making the task harder and resulting in increasing processing demands.

4.2.2 Neural correlates of temporal auditory processing of vowel length in developmental dyslexia

Like control subjects, dyslexics show bilateral hemodynamic brain activation within the auditory cortices during the phonological condition, and additional bilateral activation of the anterior insula in the temporal condition. This is in accordance to the aforementioned studies on temporal auditory processing in subjects without reading deficits. A lateralization effect or specific left hemispheric activation of the IFG in the temporal condition as observed for the control group was not found for the dyslexic group.

However, a group subtraction analysis (controls vs. dyslexics and vice versa) does not reach significance. This is somehow unexpected as on the behavioural level dyslexics clearly show lower performance in the temporal vowel length discrimination task than controls. The question remains why the observed behavioural deficit can not be found on the neural level. Maybe the statistical power is not sufficient. A tendency towards differing brain activations between dyslexics and controls can be seen in the temporal condition, though significance is not reached. To solve this problem of statistical power an additional subgroup subtraction analysis was performed. When comparing groups based on their discrimination performance (high performers with 90 and more percent correct vs. low performers with 60 and less percent correct) activation within both anterior insular cortices and the left IFG is significantly higher in the high compared to the low performing group.

With respect to the neural response of dyslexics, noticeably, the high performing group comprises with five controls and one dyslexic mostly control subjects. Though, one dyslexic participant is also found in this high performing group. Therefore one has to consider that dyslexia is unlikely to represent a single core

deficit. First, only children with multiple deficits might develop manifest literacy impairments leading to developmental dyslexia (Bishop, 2006; Snowling, 2008). Second, there might be diagnostic subgroups of dyslexic individuals that are characterized by different core deficits (Aaron et al., 1999; Heim et al., 2008; Lachmann et al., 2005; Lachmann and van Leeuwen, 2008). This problem of heterogeneity in dyslexia might also be the reason for the lack of significant results in the group subtraction analysis.

Like in the discussion of the behavioural study another explanation for the lacking group effect on the neural basis might be age. Maybe the differences between reading impaired and non-impaired subjects are much more evident in children than in adolescents and adults and not only on the behavioural but also on the neural level. However, only little is known about the development of the dyslexic brain as most of the neuroimaging studies are either performed on adults or focus on only time point and are not longitudinal.

Still, within the low performing group only dyslexic participants are found ($n = 5$), all exhibiting decreased activation patterns in the mentioned brain regions. Quite some recent studies argue for a disruption of the neural response in prefrontal/frontal regions to rapid acoustic stimuli in developmental dyslexia (Corina et al., 2001; Gaab et al., 2007; Ruff et al., 2002; Steinbrink et al., 2009; Temple et al., 2000). More precisely, on the level of the anterior insula a decreased hemodynamic activation is found for the group of low performing dyslexics during the temporal condition. This was also observed in the study by Steinbrink and colleagues (2009). In their control group, activation of the left anterior insula increased linearly with stimulus presentation rate, while activation of its right counterpart decreased with increasing presentation rate. This hemodynamic activation pattern was found for both the click and the syllable condition. In

dyslexics, in contrast, rate-dependent hemodynamic activation of the left and right insula was restricted to the click condition only and lacking for the speech stimuli. Moreover, like in this study, dyslexics generally exhibited reduced activation of both, the left and the right insular region in both conditions.

As to the neural response of the left IFG in dyslexics, the obtained findings exhibit in accordance to previous studies a decreased activation of the left IFG in low performing dyslexics during the temporal condition. For example, Gaab and colleagues (2007) investigated in their study the hemodynamic brain activation of children with and without reading deficits to complex non-linguistic stimuli with either rapid (40 msec) or slowed (200 msec) frequency transitions. An increased response to the rapid versus slow stimuli was observed in the left prefrontal cortex (PFC) of the normal-reading population. This sensitivity was lacking in dyslexics. Furthermore, group analyses exhibited greater activation among others within the left IFG in normal reading compared to dyslexic children. Gaab et al. (2007) replicated with their study the findings by Temple and colleagues (2000) that performed the same experiment with normal reading and dyslexic adults.

The observed decreased activation within this study on the level of the left and right insular cortex as well as the left IFG in low performing dyslexics during the discrimination of temporally manipulated items might reflect a functional deficit in the specialization of the prefrontal/frontal cortex for rapid temporal processing of speech parameters. Cautiously interpreted, this decreased neural response in especially the low performing subgroup of the sample of this study might be a further hint for the suggested rapid temporal processing deficit in at least a subgroup of developmental dyslexia.

5. CONCLUSION

To summarize the findings of this work, the behavioural study shows that dyslexics are impaired in their performance when only temporal information is available for vowel length discrimination.

The fact that dyslexics performed comparably to unimpaired adults when both spectral and temporal information was accessible for vowel length discrimination, but failed when only temporal information was available, can be interpreted as evidence for the existence of a temporal processing deficit in dyslexia. However, this does not preclude the possibility of an additional spectral processing deficit. It might be that dyslexics succeed when a combination of temporal and spectral cues is present for vowel length discrimination, as in the phonological condition, but that they fail when only one of these cues is available, be it spectral or temporal. Indeed, a number of psychophysical experiments have suggested that temporal as well as spectral auditory processing is impaired in dyslexia (Ahissar et al., 2000; Caccace et al., 2000; King et al., 2003; Montgomery et al., 2005; Walker et al., 2006).

On the neural level the fMRI study provides further evidence that the anterior insular cortex bilaterally, as well as the left IFG, represent parts of a neural network which is engaged in the temporal encoding of linguistic auditory material and contributes to temporal auditory processing. At least at the level of the left IFG the additional left sided activation in the control population during the temporal condition supports further the assumption of a left hemispheric superiority for rapid temporal processing.

The observed decreased activation within the anterior insula bilaterally and the left IFG in the group of low performing participants, which were all dyslexics, during the processing of temporal stimuli, might indicate a temporal auditory processing deficit in dyslexia with impaired lateralization and/or specialization of auditory frontal regions. However, one has to keep in mind that the observed activation differences occurred only for a subgroup of dyslexics. For a definite conclusion this data would have to be verified on the basis of further examinations.

Like always in research also this work does not only answer unsolved questions but also raises new ones, which would have to be clarified in future research. For example, what this work cannot answer is if developmental dyslexia is characterized by both temporal and spectral processing impairments or by temporal processing impairments alone. And moreover, if the processing impairments (either spectral, temporal or both) of dyslexics are speech specific or more basal in nature. Furthermore, one would have to repeat this experiment with children to clarify how pronounced the deficits are during the time of reading and spelling development and if some kind of intervention might be effective. And, last but not least, a further inspection of the present results by means of other examination methods like structural MRI (i.e. resting state functional connectivity, diffusion tensor imaging, voxel based morphometry,...) or EEG, which might be more sensible than fMRI to investigate temporal processing due to its higher temporal resolution, might help to complete the picture on temporal auditory processing deficits in developmental dyslexia.

6. SUMMARY

Developmental dyslexia is, with a prevalence of four to nine percent, one of the most frequent developmental disorders in childhood and adolescence. Nevertheless, the basic cause of this impairment is still not clearly understood. Researchers agree upon that poor phonological processing skills are considered as one of the core symptoms. However, it is still debated whether this deficit is the primary cause or whether it reflects a secondary symptom resulting from impairments in the processing of basic acoustic parameters of the speech signal. For instance, sensory deficiencies in rapid temporal processing are discussed as the underlying mechanism of developmental dyslexia.

The aim of this work was to scrutinize on a behavioural and neural level the aspect of temporal auditory processing in developmental dyslexia by means of a German vowel length discrimination task. The speciality of this work is that the same task and stimuli of comparable complexity were used to investigate both phonological as well as temporal processing in order to infer clear interpretations. This is lacking in many former studies. The German vowel system is particularly suitable for that purpose, as it can be used to investigate phonological as well as temporal and spectral processing within the same phoneme category. For the purpose of this work all seven German vowel pairs, which exclusively differ with respect to vowel length (e.g. /a:/ vs. /a/), were used. In German, vowel length is characterized by temporal (i.e. duration) and spectral (i.e. formant frequency) information. Vowels of a pair were embedded in consonant-vowel-consonant monosyllabic pseudo-words which were presented successively. These syllable pairs were either identical or varied but only with respect to their vowel length. Two types of differences between long versus short vowels were varied: In the phonological condition, natural vowel pairs were used, differing in their temporal

and spectral content. In the temporal conditions, a natural vowel was combined with the same but temporally manipulated (i.e. shortened or lengthened) one to keep spectral content of long and short vowels identical. Thus, the only feature of distinction between the two vowels was temporal in nature. The participants' task was to indicate whether the two presented syllables were same or different.

Twenty dyslexic adolescents and adults and twenty age matched control subjects participated first in a behavioural and half a year later in an fMRI experiment, performing the above explained task on both sessions. Results show that discrimination accuracy for phonological items was nearly perfect with no significant group difference. Yet, when participants had to decide solely on the basis of durational cues, dyslexics' performance was significantly inferior to that of controls. Regarding neural correlates hemodynamic brain activation in the temporal, but not in the phonological condition, was observed bilaterally within the anterior insular cortices in both groups and within the left inferior frontal gyrus (IFG) in controls. Group subtraction analyses did not demonstrate significant effects. However, in a subgroup analysis, participants performing low in the temporal condition showed significantly decreased activation of the insular cortices and the left IFG compared to high performing participants.

On the behavioural level the findings of this work support the notion that developmental dyslexia is associated with impairments in processing basic acoustic parameters of the speech signal, in particular, with a deficit in temporal processing. On the neural level the results indicate, that the left IFG and the insular cortices are part of a neural network involved in temporal auditory processing. Furthermore, the decreased hemodynamic brain activation within this processing network of low performing participants, which were all dyslexics, during the temporal condition, could be considered as the neural basis of the observed temporal processing deficits.

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APPENDIX

APPENDIX A

Participation information and declaration of consent

Informed consent form was obtained in line with the Institutional Review Board of the University of Ulm.

Universitätsklinik für Neurologie Geschäftsführender Direktor: Prof. Dr. Albert C. Ludolph		Abteilung Psychiatrie III / Transferzentrum für Neurowissenschaften und Lernen Ärztlicher Direktor / Leiter: Prof. Dr. Dr. Manfred Spitzer
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PROBANDENINFORMATION

Titel der Studie:

Verhaltens- und fMRT-Studie zur zeitlichen Verarbeitung von Vokalen des Deutschen

Sehr geehrte Damen und Herren,

bei der Wahrnehmung und Unterscheidung von Vokalen (Selbstlauten) spielen zeitliche Unterschiede eine große Rolle. Nehmen wir als Beispiel die gesprochenen deutschen Wörter „Ofen“ und „offen“. Diese unterscheiden sich hinsichtlich der Länge des Vokals „o“, aber auch bezüglich anderer Aspekte des Sprachsignals (z.B. Tonhöhe). Bis heute ist unklar, welche Wichtigkeit die Zeitdauerunterschiede von langen und kurzen Vokalen für die Vokalwahrnehmung und –unterscheidung haben. Hören wir z.B. auch dann „Ofen“, wenn wir das „o“ verkürzen? Bleibt es bei der Wahrnehmung von „offen“, wenn das „o“ länger gemacht wird? Um diese und ähnliche Fragen zu prüfen, haben wir für unsere Verhaltensexperimente Aufnahmen von Phantasiewörtern (z.B. „pam“) erstellt, bei denen die Dauer der in ihnen enthaltenen Vokale variiert. Neben den Originalvokalen des Deutschen werden per Computer bearbeitete Vokale eingesetzt, die in der Zeitdauer verlängert oder verkürzt worden sind. In unserem Experiment hören Sie über Kopfhörer Paare von Phantasiewörtern oder einzelne Phantasiewörter. Sie haben die Aufgabe per Tastendruck zu entscheiden, ob sich die dargebotenen Wörter gleich oder verschieden angehört haben, bzw. ob der im Wort enthaltene Vokal lang oder kurz ist. Anhand Ihrer Antworten können wir beurteilen, wie sehr die Veränderung der Zeitdauerunterschiede die Wahrnehmung von Vokalen beeinflusst.

Studien mit bildgebenden Verfahren deuten darauf hin, dass die beiden Hirnhälften unterschiedliche Funktionen bei der zeitlichen Verarbeitung von Hörreizen übernehmen. Die linke Gehirnhälfte scheint darauf spezialisiert zu sein, schnelle Reize zu verarbeiten, während langsamere zeitliche Wechsel eher von der rechten Hirnhälfte verarbeitet werden. Die meisten Erkenntnisse zu diesem Thema wurden mit nicht-sprachlichen Hörreizen gewonnen, und bisher ist noch kaum etwas darüber bekannt, wie die Zeitverarbeitung bei Sprachreizen wie Vokalen (Selbstlauten) vor sich geht. Das deutsche Vokalsystem ist besonders geeignet diese Frage zu untersuchen, weil sich im Deutschen eine Reihe von Vokalen hinsichtlich der Zeitdauer unterscheiden (vgl. z.B. die gesprochenen Wörter „Miete“ und „Mitte“, „Rate“ und „Ratte“). Wir möchten im zweiten Teil unserer Studie untersuchen, wo verschiedene Vokallängen im Gehirn verarbeitet werden. Dazu nutzen wir die Methode der funktionellen Kernspintomographie (fMRT), mit der Bilder vom „arbeitenden“ Gehirn erzeugt werden können. Die Studienteilnehmer bekommen erneut über Kopfhörer Pseudowörter dargeboten. Da diese Wörter bezüglich der Vokallänge variiert werden, können wir durch Auswertung der Gehirnbilder Einsichten darüber gewinnen, wie Zeitdauerunterschiede zwischen Vokalen vom Gehirn verarbeitet werden.

Universitätsklinik für Neurologie Geschäftsführender Direktor: Prof. Dr. Albert C. Ludolph		Abteilung Psychiatrie III / Transferzentrum für Neurowissenschaften und Lernen Ärztlicher Direktor / Leiter: Prof. Dr. Dr. Manfred Spitzer
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Die Methode des fMRT nutzt Radiowellen in einem Magnetfeld zur Erzeugung der Bilder (keine Röntgenstrahlen oder Radioaktivität). Die Kernspintomographie ist ein modernes Untersuchungsverfahren, das weltweit in vielen Krankenhäusern eingesetzt wird. Bei sachgemäßer Durchführung sind von diesem etablierten Untersuchungsverfahren keine gesundheitlichen Gefahren oder Risiken zu erwarten. Bei der von uns verwendeten Feldstärke sind bislang keine schädigenden Wirkungen aufgetreten oder bekannt geworden. Die sachgemäße Durchführung der Untersuchung wird durch einen speziell ausgebildeten Arzt gewährleistet. Erfahrungsgemäß scheint das Engegefühl im Tomographen, das allerdings relativ rasch abklingt, für einige Menschen am unangenehmsten zu sein. Im Untersuchungsraum herrscht während der Messung ein Magnetfeld. Metallteile können, wenn sie in das Magnetfeld kommen, Unfälle verursachen. Wir werden deshalb vor Beginn der Untersuchung durch eine Befragung prüfen, ob sich irgendwelche Metallteile an oder in Ihrem Körper befinden oder andere Gegenanzeigen bestehen, die eine Kernspinuntersuchung bei Ihnen nicht zulassen.

FREIWILLIGKEIT:

An diesem Forschungsprojekt nehmen Sie freiwillig teil. Ihr Einverständnis können Sie jederzeit und ohne Angabe von Gründen widerrufen. Alle bis dahin erhobenen Daten und Proben werden vernichtet.

ERREICHBARKEIT DES PROJEKTL EITERS:

Sollten während des Verlaufes des Forschungsprojektes Fragen auftauchen, so können Sie jederzeit als Ansprechpartner Dr. Axel Riecker unter der Telefonnummer 0731 / 177 – 5242 erreichen.

VERSICHERUNG:

Während der Teilnahme an dem Forschungsprojekt genießen Sie Versicherungsschutz. Es gelten die allgemeinen Haftungsbedingungen.

Einen Schaden, der Ihrer Meinung nach auf die Untersuchung zurückzuführen ist, melden Sie bitte unverzüglich dem Projektleiter.

SCHWEIGE PFLICHT/DATENSCHUTZ:


Alle Personen, welche Sie im Rahmen dieses Projektes betreuen, unterliegen der Schweigepflicht und sind auf das Datengeheimnis verpflichtet. Die studienbezogenen Untersuchungsergebnisse sollen in anonymisierter Form in wissenschaftlichen Veröffentlichungen verwendet werden.

Soweit es zur Kontrolle der korrekten Datenerhebung erforderlich ist, dürfen autorisierte Personen (z.B.: des Auftraggebers, der Universität) Einsicht in die studienrelevanten Daten nehmen.

Sofern zur Einsichtnahme autorisierte Personen nicht der oben genannten ärztlichen Schweigepflicht unterliegen, stellen personenbezogene Daten, von denen sie bei der Kontrolle Kenntnis erlangen, Betriebsgeheimnisse dar, die geheim zu halten sind.

.....
Datum

(Name des aufklärenden Projektmitarbeiters)

Universitätsklinik für Neurologie		Abteilung Psychiatrie III / Transferzentrum für Neurowissenschaften und Lernen
Geschäftsführender Direktor: Prof. Dr. Albert C. Ludolph		Ärztlicher Direktor / Leiter: Prof. Dr. Dr. Manfred Spitzer

EINWILLIGUNGSERKLÄRUNG

Titel der Studie

Verhaltens- und fMRT-Studie zur zeitlichen Verarbeitung von Vokalen des Deutschen

Inhalt, Vorgehensweise, Risiken und Ziel des oben genannten Forschungsprojektes sowie die Befugnis zur Einsichtnahme in die erhobenen Daten hat mir ausreichend erklärt.

Ich hatte Gelegenheit Fragen zu stellen und habe hierauf Antwort erhalten. Ich hatte ausreichend Zeit, mich für oder gegen die Teilnahme am Projekt zu entscheiden.

Eine Kopie der Probandeninformation und Einwilligungserklärung habe ich erhalten.

Ich willige in die Teilnahme am Forschungsprojekt ein.
(Name des Probanden)

.....
Ort, Datum (Unterschrift des Probanden)

INFORMATION UND EINWILLIGUNGSERKLÄRUNG ZUM DATENSCHUTZ

Bei wissenschaftlichen Studien werden persönliche Daten und medizinische Befunde über Sie erhoben. Die Speicherung, Auswertung und Weitergabe dieser studienbezogenen Daten erfolgt nach gesetzlichen Bestimmungen und setzt vor Teilnahme an der Studie folgende freiwillige Einwilligung voraus:

1. Ich erkläre mich damit einverstanden, dass im Rahmen dieser Studie erhobene Daten/ Krankheitsdaten auf Fragebögen und elektronischen Datenträgern aufgezeichnet und ohne Namensnennung verarbeitet werden
2. Außerdem erkläre ich mich damit einverstanden, dass eine autorisierte und zur Verschwiegenheit verpflichtete Person (z.B.: des Auftraggebers, der Universität) in meine erhobenen personenbezogenen Daten Einsicht nimmt, soweit dies für die Überprüfung des Projektes notwendig ist. Für diese Maßnahme entbinde ich den Arzt von der ärztlichen Schweigepflicht.

.....
(Name des Probanden)

.....
Ort, Datum (Unterschrift des Probanden)

APPENDIX B

Measurement of reading abilities

Real and pseudo word reading by Schulte-Körne (2001):

Reading abilities were tested by means of a German reading test for adults developed by Schulte-Körne (2001). This test measures reading time and reading errors for real words and for pseudo-words. Unfortunately the test is not standardized and normed. However, no other German reading tests existed during time of examination for the age group of the participating sample of this study. Nevertheless, the test was often applied by our and other research groups so that reference data exist. To be assigned to the dyslexic group in this study, participants had to score below two standard deviations of the mean performance of the controls within all four reading measures.

Name: _____

Leselisten: Reale Wörter	Fehler/Auslassung	Leselisten: Nichtwörter	Fehler/Auslassung
Namen		Momen	
Verhältnisse		Werpültnasse	
Meinung		Tienang	
Gelegenheit		Diligentrut	
Herzog		Gerzug	
Paragraphen		Benaplieren	
Umstand		Fartamm	
Forderungen		Kuntaplaste	
Unrecht		Uplecht	
Eigenschaften		Löckelzarften	
Praxis		Stuvis	
Anerkennung		Inerfausing	
Prozeß		Hetreß	
Beschaffenheit		Lemfassdartaut	
Phosphor		Drossgar	
Philosophie		Klinarogtal	
Kultur		Nislum	
Verbesserung		Backtulising	
Kohlen		Lopdap	
Gefangenen		Denasrehma	
Pulver		Verras	
Übersetzung		Ännarzukung	
Ketten		Lullan	
Oberfläche		Odarklaste	
Ladung		Fonmas	
Übertragung		Üferbraling	
Gründung		Mücklaun	
Beteiligung		Fatelaunung	
Messer		Ressam	
Korrespondenz		Kirasklundanz	
Drama		Pafta	
Operation		Adarkanta	
Anmut		Emnat	
Verteidiger		Waligartur	
Substanz		Paksrann	
Vollkommenheit		Vannlummenkaut	
Venus		Storvitz	
Destillation		Arexmarte	
Vorsitz		Suvons	
Exemplar		Tilladitung	
Effekt		Tekkfatt	
Experiment		Mengximunte	
Porträt		Hillhott	
Quotisierung		Trefedunto	
Billet		Trätrop	
Patriarchen		Archelpato	
Gassen		Sissmen	
Dividenden		Siquontiret	

Summe richtig gelesene Wörter:
(von 48)

Summe richtig gelesene Nichtwörter:
(von 48)

Zeit:

Zeit:

APPENDIX C

Measurement of writing abilities

Rechtschreibungstest-RT by Kersting & Althoff (2004):

Spelling was measured by means of the German standardized spelling test “Rechtschreibungstest” for adults by Kersting and Althoff (2004). To qualify as dyslexic, participants had to score below one standard deviation of the mean performance of the reference population (percentage rank < 16). To be assigned to the control group, participants had to show average or above average spelling skills (percentage rank > 31).

Exemplarily, the completed spelling test of one dyslexic participant of this study is shown here.

M. Kersting & K. Althoff RT		Diktat „Rummelplatz“	
---------------------------------------	--	-----------------------------	--

Name: [REDACTED] Vorname: [REDACTED]

Alter: 16 Code-Nr.: _____ Datum: 24.5.2007

Anweisung zum Diktat „Rummelplatz“

Tragen Sie bitte zunächst oben ein: Ihren Namen, Vornamen, Ihr Alter in Jahren, ggf. Ihre Codenummer sowie das Datum von heute.

Sie werden auf diesem Bogen einen Text vorfinden, in dem viele Stellen ausgelassen sind. Sie sollen diese Lücken in folgender Weise ausfüllen: Ich lese Ihnen den Text langsam vor, Sie lesen ihn still und aufmerksam mit. Wenn wir an einer Lücke angekommen sind, nenne ich Ihnen die fehlenden Wörter, und Sie tragen sie an dieser Stelle deutlich und richtig geschrieben ein. Es kommen nur Wörter vor, die nach den bisherigen Rechtschreibregeln und nach den neuen Regeln dieselbe Schreibweise haben.

Zunächst ein Beispiel: Ich diktiere, und Sie schreiben bitte jetzt sofort mit.

Es ist besser, einen Spatz in der Hand zu halten als eine Taube auf dem Nach.

Beachten Sie, dass in die dritte Lücke zwei Wörter eingetragen werden. Auch auf den folgenden Seiten gibt es einige Lücken, in die zwei Wörter einzutragen sind.

In gleicher Weise wird der ganze Bogen bearbeitet. Schreiben Sie zügig mit. Sie haben keine Zeit, lange zu überlegen. Wenn Sie ein Wort beim Vorlesen nicht verstanden haben, melden Sie sich bitte sofort und fragen nach. Ich diktiere es dann noch einmal. Der ganze Text wird im Übrigen nur einmal vorgelesen. Füllen Sie daher alle Lücken sofort aus.

Beachten Sie:

- Diktierte Zahlen sind immer in Worten auszuschreiben!
- Schreiben Sie deutlich, aber bitte keine Druckschrift!
- Es muss eindeutig zu erkennen sein, ob Sie die Wörter groß oder klein, getrennt oder verbunden geschrieben haben. Alle Zweifelsfälle, auch unklare Verbesserungen werden als Fehler gewertet! Wenn Sie etwas korrigieren wollen, streichen Sie das Wort durch und schreiben es neu.
- Ihre Handschrift muss für die Auswertung zwar gut lesbar sein, eine Bewertung des Schriftbildes erfolgt aber nicht.

F (RW)	51	SW	75	PR	0,6
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Rummelplatz

Lieber Alexander!

Wir wollten uns Wöchentlich schreiben, doch weiß ich heute wenig
 heute zu berichten. Vielleicht wird dich aber ein Erlebnis interessieren,
 das ich am vergangenen Sonntag – um gegen vier Uhr – hatte. Ich
 verspürte Langeweile, hatte jedoch wenig Interesse, meine Aufgaben für
 das Gymnasium zu erledigen. Stattdessen fuhr ich mit Bastian zum Rummelplatz.
 Dort stürzten wir uns 1. Flur in die Menge und bestiegen
prompt ein Karussell, das sich mit wechselndem Tempo und
 lauter Musik drehte. In der Nähe stand ein Mann in ausgefranstem
Frag, auf dem Kopf einen schäbigen Zylinder. Er schlug in schnellem
Kakt auf eine Pauke und versuchte, die Menge zusammen zu trommeln.
 Dann legte er ein Mädchen auf ein Nagelbrett und tat mit großem Limtaufwand
 und gehörtesten Worten das, dass er fühlt und wollen
 seines Opfers ganz ausschalten und es zu den überwuch überwucherten Leistungen
 veranlassen könne. Er trat sehr gewohnt auf, und etwa zwei Autrent aus
 der Menge ruhen auf den Schwindel herein. Allerdings verließen die selben

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// das Zelt nachher mit Entsetzten Gesicht. Bastian, der überglücklich
 // ist, zog mich trotz meines widerstehen zu einer mit Leinwand behängten
 // Wahrsagerin. Diese Weißagte aus den Handlinien und Broderie
 // grausige Ereignisse. Nicht weit davon entfernt brun ein alter Mann, mit
 // Brusthaare Gesicht und von offenbar fragwürdigem Karakter,
 Gewehre an, wie man sie auch zur Jagd verwendet. Man konnte damit
 // durch ein auflöser Loch nach 1 auf und abstrich Ballons
 // schießen. Es gelang dem alten nicht, Lumpentier
 // zu wecken und Schützen anzulocken. Die Mural des
 // vergeblichen wartens vergrünzte ihn. Die meisten Leute versammelten
 // sich in der vor einem qualmenden Feuer, auf dem Würstchen schmorten.
 // Sie waren zweifeln das verlockende Ziel, und auch wir konnten
 // nicht widerstehen. Als sich der Platz leerte, erinnerte ich
 // mich heimlich meiner Hausaufgaben. Da auch meine ganze Baruchal
 // nur noch bechrendechtig Cent betrug, gingen wir nach Hause. Um einem

Bitte umblättern und auf der Rückseite weiter arbeiten.

1. verweiß zu entgehen, brachten wir meiner Mutter ein verzürtes Lebkuchenherz

2. mit. Ich hoffe, dass ich dir Morgenfrüh etwas vernünftigeres schreiben kann.

4
51

Dein Michael

Legen Sie jetzt bitte die Stifte fort, und drehen Sie den Testbogen um!

4

APPENDIX D

Stimuli utilized in this study

Durations (msec) of long and short vowels within the pseudo-word syllables /fVp/ and /nVp/, grouped according to vowel height. Syllables were spoken by a trained female speaker and produced in continuous speech with normal speaking rate and without stress.

Syllable	Vowel height	Vowel pair	Vowel duration (msec)		Difference (msec)
			long	short	long – short
fVp	high	/i:-ɪ/	91	52	39
		/y:-ʏ/	97	54	43
		/u:-ʊ/	100	58	42
	mid	/e:-ɛ/	109	68	41
		/ø:-œ/	120	70	50
		/o:-ɔ/	132	78	54
	low	/a:-a/	140	75	65
nVp	high	/i:-ɪ/	90	50	40
		/y:-ʏ/	99	52	47
		/u:-ʊ/	104	56	48
	mid	/e:-ɛ/	110	64	46
		/ø:-œ/	121	70	51
		/o:-ɔ/	124	72	52
	low	/a:-a/	143	75	68

APPENDIX E

Experiment instructions given in oral and written form

Orally given instructions:

Experiment zur Vokallängendiskrimination: Mündliche Instruktionen

In unserer Studie geht es darum herauszufinden, wie gut Wörter mit Unterschieden in der Vokallänge beim Hören auseinandergehalten werden können.

Im Deutschen unterscheiden wir zwischen langen und kurzen Vokalen bzw. Selbstlauten, also z.B. einem langen und kurzen „i“ oder einem langen und kurzen „a“. So unterscheiden sich die Wörter Miete und Mitte beim Hören z.B. nur in der Länge des Vokals „i“ und die Wörter Rate und Ratte nur in der Länge des Vokals „a“.

Übungsphase: Wir erklären und üben die Aufgabe erst einmal mit echten Wörtern. Es werden Ihnen immer über Kopfhörer zwei Wörter hintereinander vorgespielt. Diese können sich entweder in der Länge des Vokals unterscheiden, oder exakt gleich sein. Wenn die Wörter gleich sind (z.B. Schal – Schal), dann drücken Sie bitte die Gleich (=) -Taste. Sind die Wörter verschieden, weil sie einen verschieden langen Vokal haben (z.B. Schal – Schall), dann drücken Sie bitte die Verschieden (≠) -Taste.

Bitte versuchen Sie, immer möglichst schnell und möglichst richtig zu antworten und benutzen Sie zum Antworten immer die Daumen der linken und rechten Hand.

Bitte warten Sie dabei ab, bis das Wort zu Ende gesprochen wurde.

In der Übungsphase ertönt immer ein Warnton, wenn Sie den falschen Knopf drücken.

Wenn Sie also nichts hören, dann haben Sie die richtige Entscheidung getroffen.

In unserer richtigen Aufgabe werden keine echten Wörter verwendet, sondern Phantasie- oder Quatschwörter, d.h. Wörter, die keine Bedeutung haben (z.B. „pam“). Grundsätzlich geht die Aufgabe genau wie vorher: Sie hören zwei Phantasiewörter hintereinander und sollen durch Tastendruck entscheiden, ob die beiden Wörter gleich oder verschieden waren. Der Unterschied kann manchmal nur sehr gering sein, weshalb Sie ganz genau hinhören müssen, um entscheiden zu können ob die Länge der Vokale gleich oder verschieden ist. Auch hier kommt beim Üben wieder ein Warnton, wenn Sie die falsche Taste drücken.

Experiment: Haben Sie die Aufgabe verstanden? Können Sie alle Stimuli gut hören? Bei den nun folgenden Aufgaben gibt es keinen Warnton mehr, der Ihnen sagt, ob Sie richtig oder falsch geantwortet haben. Da die Aufgabe insgesamt etwas länger dauert, haben wir sie in vier Teile eingeteilt, zwischen denen wir eine kurze Pause machen können. Bitte denken Sie noch mal daran, dass es wichtig ist, ganz genau hinzuhören und dass Sie immer möglichst schnell aber auch möglichst richtig antworten sollen.

Written instructions:

Experiment zur Vokallängendiskrimination

Bitte lesen Sie sich die folgenden Anweisungen in Ruhe und aufmerksam durch.

In unserer Studie geht es darum herauszufinden, wie gut Wörter mit Unterschieden in der Vokallänge beim Hören auseinandergehalten werden können.

Im Deutschen unterscheiden wir zwischen langen und kurzen Vokalen (Selbstlauten), also z.B. einem langen und kurzen „i“ oder einem langen und kurzen „a“. So unterscheiden sich die Wörter *Miete* und *Mitte* beim Hören z.B. nur in der Länge des Vokals „i“ und die Wörter *Rate* und *Ratte* nur in der Länge des Vokals „a“.

Über Kopfhörer werden Ihnen nun kurze Quatschwörter-Paare (also Wörter, die keine Bedeutung haben) vorgespielt. Die Paare sind entweder gleich oder unterscheiden sich, jedoch nur bezüglich der Länge ihrer Vokale (Selbstlaute). Ihre Aufgabe ist es zu entscheiden ob die zwei dargebotenen Quatschwörter gleich oder ungleich sind (d.h. ob sie sich gleich oder ungleich anhören) und die entsprechende Taste zu drücken.

Die = Taste steht für gleich, die ≠ Taste steht für ungleich.

Ein Beispiel: Ist ein Paar zu hören, das unterschiedlich lange Vokale hat, wie z.B. „*pamm* – *pahm*“, drücken Sie bitte die ≠ (ungleich) Taste. Ist ein Paar zu hören, in dem der Vokal gleich lang ist, z.B. „*pamm* – *pamm*“, drücken Sie bitte die = (gleich) Taste.

Vor Beginn des eigentlichen Experiments gibt es eine Übungsphase. Hier soll gezeigt werden worum es geht und worauf Sie achten sollen. Zur Verdeutlichung wird erst mit echten Wortpaaren geübt. Danach folgt eine Einübungsphase mit Paaren von Quatschwörtern, wie sie auch im Experiment verwendet werden.

Ihre Aufgabe ist es, wie bereits erwähnt, zu entscheiden ob die Wörter gleich oder ungleich klingen und die entsprechende Taste zu drücken. Ist z.B. das Paar „*Wahl* – *Wall*“ zu hören, würde die Antwort „ungleich“ lauten, d.h. Sie müssten die ≠ Taste drücken. Wenn Sie das gleiche Paar „*Wahl* – *Wahl*“ hören, müssten Sie die = Taste drücken.

Während der Übungsphase haben Sie jederzeit die Möglichkeit Fragen zu stellen.

Zusätzlich hören Sie als Rückmeldung einen Warnton wenn Sie falsch gedrückt haben.

Später im Experiment gibt es keine Rückmeldung mehr.

Das Experiment ist in vier Blöcke eingeteilt, so dass zwischendurch immer wieder Zeit für Pausen und Fragen besteht.

Wichtig:

Bitte versuchen Sie so schnell und so korrekt wie möglich zu antworten!

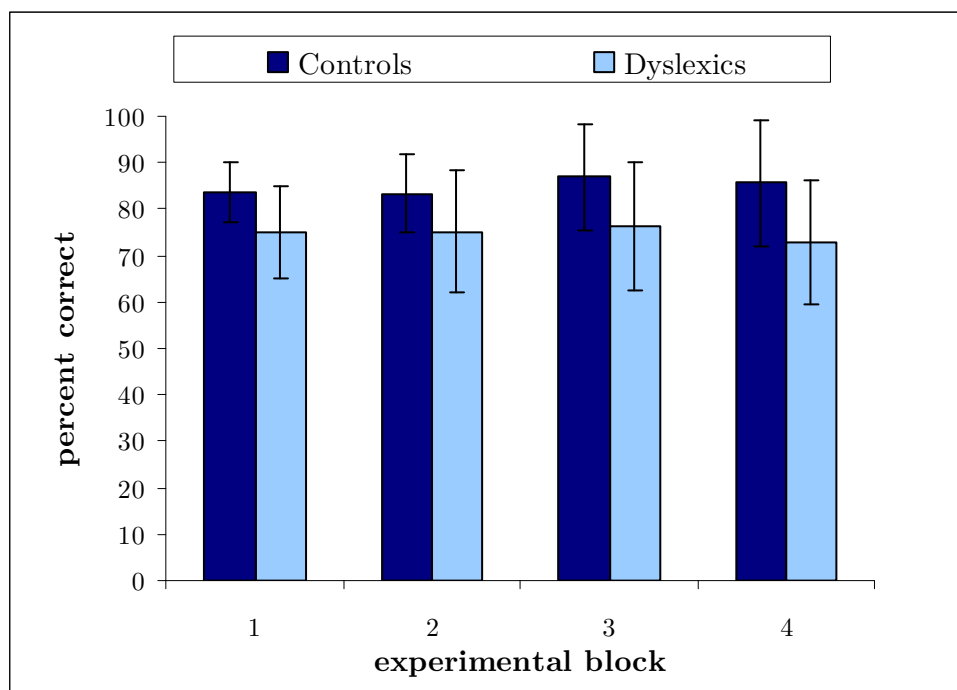
Noch Fragen?

Danke für Ihr Interesse und Ihre Mitarbeit!

APPENDIX F

Experiment 1 – Discrimination performance per block

Discrimination performance (irrespective of stimulus type) was analyzed for both groups in dependence of each experimental block to control for attentional decline over the course of the experiment. No significant decline in any group in performance from block one to block four could be observed.



COMMENT

This thesis formed the basis for two international publications*. The behavioural experiment with its data and results was published in the journal “Reading and Writing”. The fMRI experiment with its data and results was published in the journal “Brain and Language”. On both publications Katarina Groth, the author of this thesis, is also the first author of the papers. On the second publication Claudia Steinbrink is additionally considered as first author. On this second publication Katarina Groth is also considered, together with Axel Riecker, as corresponding author.

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Publications:

*Reprinted from Reading and Writing 24, Groth, K., Lachmann, T., Riecker, A., Muthmann, I., Steinbrink, C., Developmental dyslexics show deficits in the processing of temporal auditory information in German vowel length discrimination, pp. 285-303, Copyright 2011, with permission from Springer Science and Business Media.

* Reprinted from Brain and Language 121, Steinbrink, C., Groth, K., Lachmann, T., Riecker, A., Neural correlates of temporal auditory processing in developmental dyslexia during German vowel length discrimination: An fMRI study, pp. 1-11, Copyright 2012, with permission from Elsevier.

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CURRICULUM VITAE

In der Online-Version wurde der Lebenslauf aus Gründen des Datenschutzes entfernt.

PUBLICATIONS (research articles)

- Sachse, S., Budde, N., Rinker, T. & Groth, K. (2012). Evaluation einer Sprachfördermaßnahme für Vorschulkinder. *Frühe Bildung*, 1, 194-201.
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