Abnormal Oscillatory Brain Responses in Dyslexic children with Poor Categorical Perception

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Abstract: The condition of dyslexia has been associated with problems in speech perception, particularly in the processing of speech signals (e.g., phonemes). Speech signals contain information on different time scales. For instance, while rapid spectral changes as formant transitions may occur on time scale (20-40ms), syllabic and prosodic information occur on a time scale of (150-300ms). Therefore, the segmentation of the auditory stream into discrete representations is a prerequisite for speech perception, According to Peoppel (2003); the input speech signal has a neural representation that is bilaterally symmetric at an early representational level; however it is elaborated asymmetrically in the time domain. Consequently, it has suggested that temporal integration in different windows is reflected as oscillatory neuronal activity in different frequency bands. In this study, we are testing if the temporal integration is reflected as oscillatory activity in different frequency bands by mapping focal slow waves in the delta (1.5-4Hz) frequency band. We used magnetoencephalographic (MEG) source imaging in a sample of 19 dyslexic children with poor categorical perception and 14 controls while listening passively to syllables /ba/ and /da/. Dyslexic children with poor categorical perception differ significantly in the density of magnetic slow waves produced by the two hemispheres. To illustrate, dyslexic children with poor categorical perception showed elevated production of focally generated slow waves (1-4Hz), predominately in the left hemisphere as compared to controls. The results suggest altered segmentation processes of speech sounds in a subset of children with dyslexia.

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1. Introduction

Dyslexia is a neurodevelopmental disorder that causes persistent difficulties in the acquisition of written language abilities such as reading,writing and spelling. Difficulties associated with dyslexia persist into adulthood, causing measurable language processing deficits in adults. Because written-language processing involves multiple linguistic, visual, and attentional processes, it is probable that variable patterns of weakness may contribute to dyslexia(Dole et al, 2014). However, the best understood cause of dyslexia is a weakness in phonological awareness (PA) - make use of the sound structure of language to perform oral and written language manipulation (e.g., Wagner & Trogesen, 1987). Across languages, children with dyslexia have poor phonological processing skills, leading to the dominant phonological core deficit of the hetregeneous disorder (Stanovich, 1998). For years, evidence has been provided by correlational, longitudinal and intervention studies as to the role of high levels of phonological awareness in enhancing reading achievement not only in individuals with dyslexia, but also in middle and lower level readers (e.g., Fox & Routh, 1976; Rack *et* al., 1994; Mains *et al.* , 1997; Shaywitz, 1998; Snowling, 2000; Mody, 2003; Castles & Coltheart, 2004).

According to McBride-Chang's integrated model (1996), there are associations between phonological processing skills, speech perception and the word reading process. These associations have been supported to be based on indirect relations in the sense that the speech perception's association with word reading is mediated by the associations of speech perception with the phonological processing skills included. Moreover, deficits in analyzing the phonological structure of spoken language have been attributed to possibly inadequate representations of phonemes resulting from basic perceptual deficits (Tallal & Piercy, 1973; Tallal, 1980; 1984; Mains *et al.,* 1997). In line with these impoverished phonological representations, one may expect deficits in tasks where individuals have to assign speech sounds to phonemic categories or where they have to determine whether acoustically-similar speech sounds belong to the same category (For more details, see. Vandermosten *et* al., 2011). Inspection of the literature on categorical perception in dyslexia confirms that individuals with dyslexia performed more poorly than control subjects (Tallal, 1980; Reed, 1989; Mains *et al.,* 1997; Mody, 2003;

Sernicales *et al.* , 2001). Results indicated that due to their deficiencies in processing the rapid formant transition (fast frequency changes) of stop-consonants, which lasts about 40 ms, children with dyslexia performed poorer than typically developing children in categorizing speech sounds or distinguishing consonant-vowel (CV) syllables like /ba/ and /da/.

Taken together, it has been inferred that dyslexic readers suffer from a basic, non-linguistic deficit in temporal resolution of rapidly changing auditory stimuli that impairs speech perception. As a result, this deficit contributes to inadequately defined sound and representations which interfere with phonology processing (Reed, 1989; Tallal *et al.,* 1993; Vulletino *et* al. , 2004).

Since the late 19^{th} century (Broca, 1861; Wernicke, 1874), speech processing has been investigated with a consideration to the functional hemispheric asymmetry of the auditory cortex (In: Okamoto *et* al., 2009). Later, evidence for the dominance of the left hemisphere in speech processing has been originally provided by observations of patients with neurological deficits at both the behavioral and the neurological level. Studies employing recent neuroimaging techniques as functional magnetic resonance imaging (FMRI) (e.g., Belin, *et* al., 2000) and MEG (e.g., Eulitz, *et* al., 1995) have supported the view that speech is dominantly processed in the left hemisphere. However, for lower level perceptual functions, cortical lateralization has been more ambiguous (Poeppel, 2003).

Based on investigations of monkeys and human beings, Merzenich, *et* al., 1993) have addressed the neural mechanisms involved in the auditory cortex. They proposed that neurons respond strongly to successively presented temporal stimuli only when inputs are "chunked" in time periods (amplitude modulation (AM) cycle lengths) extending from about 50 to 200 ms in cortical A1 or from about 200 to 500ms in a series of secondary auditory cortical fields. The A1 temporal chunking is perfectly appropriate for the analysis of inputs at the input rates of speech phonemes, while the longer best-AM periods of most "secondary" cortical fields blanket the integration time periods appropriate for receiving signals at syllable rates. Consequently, it was suggested that insufficiently developed or degraded representational maps, assumed to be centered in cortical per-Sylvian regions, result in noisier processing, which then would require more time for correct recognition of phonemes and consequently words (Merzeinch *et al.,* 1993; Merzenich *et al.,* 1996; Wright, *et* al., 1997).

Additionally, a growing body of neuroimaging research has led to the emergence of several models which deal with the question of what exactly is computed in left and right auditory areas (functional segregation) during speech and non-speech processing (Giraud, 2000; Hall *et* al., 2002; Zatorre & Belin, 2001; Zatorre *et* al., 2002; Zatorre, 2003). On the basis of psychophysical and neuroimaging data, Zatorre and his colleagues have argued that right hemisphere, namely right temporal superior temporal areas, is specialized for the analysis of the spectral properties of signals (e.g., pitch changes), while left hemisphere areas are better suited for the processing of rapid temporal modulation (Zatorre & Belin, 2001; Zatorre, Belin & Penhune, 2002; Zatorre, 2003). This finding has been also consistent with Tallal *et al.* (1993) as it asserts the basic notion that there is a leftward bias in the analysis of rapid spectral changes.

On the other hand, functional asymmetries in the auditory domain have been assumed to be related simply to the time frames over which auditory information is processed in each of the hemispheres (Jamison *et* al., 2005). It is uncontroversial that the information contained in speech signals occurs on multiple time scales. For instance, according to Poeppel and his colleagues (2003; 2008) speech processing requires the segmentation of an acoustic stream to generate matches with stored representations of phonemes whereby this process would rest on signal analyses occurring concurrently on two time scales. To illustrate, rapid spectral changes such as the formant transition associated with place-of- articulation information may occur on time scales on the order of ~20-80 ms for its segmental level. In contrast, syllabicity and prosodic phenomena would require a longer temporal integration of ~150-300ms, i.e., neural mass activations lasting for the corresponding time windows. In adopting this view, the authors have proposed to resolve the controversial issue of the possible relation between temporal processing and speech perception, in general and phonetics and phonology, in particular.

In principle, while a long time window chosen for sound signal analysis yields high frequency resolution but comparably poor temporal resolutions, a short time window results in high temporal but relatively poor frequency resolution. Accordingly, there must be a trade-off between spectral and temporal auditory processing precision, which would manifest within the hemispheres and differ between the hemispheres, leading to relative temporal or spectral processing hemispheric specialization, respectively (Okamoto *et al.,* 2009).

Based on the aforementioned findings, we argue that multi-time resolution processing- in the context of which segmentation occurs subsequently on segmental and syllabic time scales-are reflected as oscillatory neuronal activity in different frequency bands. Hence, we predicted that focal slow waves generated in the 1.5-4 Hz frequency (delta band) would indicate the processes at short temporal integration windows during speech processing. Therefore, the goal of the present study was to investigate if a noisy representation of phonemes, and with it a corresponding categorical perception deficit, may stem from deficits in temporal integration and segmentation in the auditory cortex. The results of this study were expected to reveal perceptual deficits in certain temporal and spectral sound contexts rather than a general deficit in the presentation of rapidly presented sounds in dyslexic children with categorical perception deficits.

Abnormal patterns of slow waves have been consistently reported in reading-impaired children. Enhanced levels of delta and theta have been most consistently found in temporal and frontal areas, with predominance in the left hemisphere of impaired readers (Harmony, *et* al., 1990; Penolazzi, *et* al., 2008) and have been interpreted as a marker of dysfunctional linguistic processing (Penolazzi *et al.,* 2008). Using magnetic source imaging, we calculated the distribution of focal generators of slow waves separately for brain regions while subjects performed a simple phoneme discrimination task. We tested if impairments of the sub-lexical phonological representation level are related to altered laterality patterns of magnetic slow activity in temporal brain regions. It is noteworthy that the use of neuromagnetic rather than neuroelectric activity has the advantage that widespread generators which typically have radial orientation (as activity in opposing walls of a sulcus would cancel out) go largely undetected by the measurement, enhancing relatively the more specific tangentially oriented neural sources (Elbert, 1998; Wienbruch, 2007).

2. Method and materials

2.1. Generation of sample

All together 68 children were either in the 3rd or 4th grade in elementary schools in and around the city of Konstanz, Germany were recruited for the current study. It is assumed here that in about three or four years of formal tuition even children with poor literacy development had a good chance to develop reasonable non-lexical and lexical procedures for their reading and spelling. The current sample is a sub-sample of Paul, *et* al., 2006). Therefore, we followed the same criteria of Paul *et al.* (2006) for classifying a child as either dyslexic or control. To sum, a dyslexic child was chosen based on: 1) teachers' informal assessment and parents' self–report of the children's weaknesses in literacy skill; 2) a performance which is significantly below the normative sample (e.g., <50 *T*-values) on a test battery(see below the materials) including not only literacy skills (reading and spelling), but also phonological abilities (e.g., Mottier Test) and categorical perception (phoneme identification); and 3) a normal development of nonverbal IQ(with IQ 85 or above). Further, subjects who showed a history of co-morbid disorders including depression, neurological conditions or ADHD, were excluded. 19 dyslexic children with poor categorical perception (C.P.)(40% of the dyslexic sample) and 11 ccontrols without any deficits have finally been selected for the current study after giving informed consent. Demographic variables have been controlled for the subgroups (a) age (controls 9.1 ± .60SD, individuals with dyslexia 9.3± .51SD); (b) gender (controls 50%, individuals with dyslexia 58% male); and (c) handedness (controls 100%, individuals with dyslexia 90% right-handed).

Table 1. Means and standard deviations of the two groups on the whole behavioural test battery.

	Controls		*Dyslexics with poor C.P.*	
	M	*±SD*	*M*	*±SD*
SPM	65.5	13.03	46.21	6.28
DRT	58.64	5.73	36.81	4.99
ZLT accuracy%	96	.02	87	.078
ZLT reading time(w/s)	.66	.19	1.57	.86
Word reading accuracy%	91	.06	73	.14
Word reading time(w/s)	70.71	20.04	188.47	90.96
PseudoWord accuracy	.76	.11	.47	.15
PseudoWord reading time	111.93	23.73	249.53	132.609
Mottier Test	.83	.11	.60	.14
Dictation	.9315	.05	.74	.13
C.P.	31.95	2.12	18.18	4.53

Crucially, the final selection of these subgroups was based on the children performance on a categorical perception task (CP), which represents "phonemic identification", served as criterion for admission into the dyslexic with categorical perception deficit and the control groups. In this task, a child was asked to identify stimuli of a 10-item /ba/-/ba/, continuum into the phonemic categories. A high perception index indicates reliable and correct categorization of the syllables (Paul *et al.,* 2006). Means of identification percentage of both /ba/ and /da/ syllables in controls as compared to dyslexic children with poor categorical perception across trials are represented (Fig. 1).

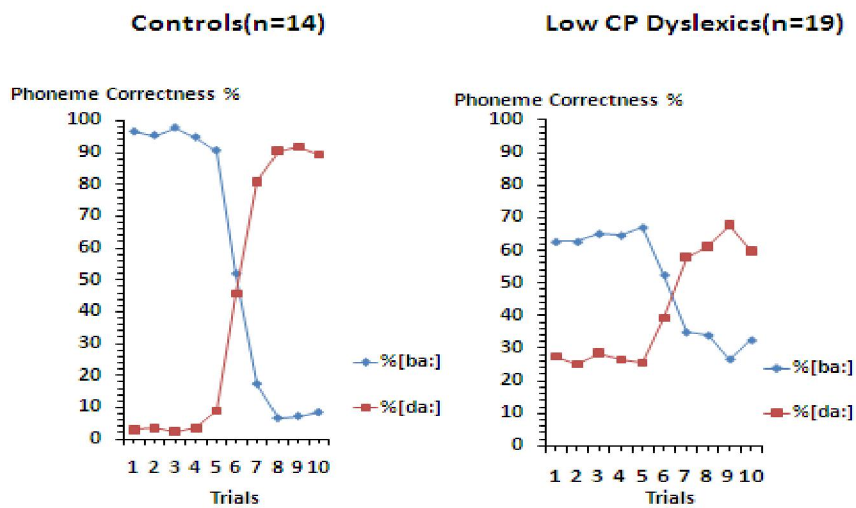

Figure 1. Categorical perception index. Means of identification percentage of both /ba/ and /da/ syllables in controls as compared clinical dyslexia subjects across trials.

2.2. Assessment

A battery of tests served to measure language skills. The test battery tests assessed nonverbal IQ, literacy skills, phonological processing abilities and categorical perception.

2.2.1. Literacy Measures

Spelling skills were measured by the diagnostic test of correct spelling, Diagnostischer Rechschreibtest (DRT) for grades 3 and4 (Grund *et al.,* 1994; Müller, 1997). In this test, a child has to spell out the dictated word and write it in the gaps of the sentences. To test reading skills, children were given Grissemann's (2000) Zurich Reading Test (Zürcher Lesetest, ZLT), an individual reading aloud test. In this test, children were asked to read aloud lists of words and small passages. Further, children were also asked to read aloud a list of 50 words which vary in complexity (Paul *et al.,* 2006). For reading tests, scores were based on both time and accuracy. Response times were recorded to determine seconds needed to read a word, list of words or paragraphs. Measures of accuracy represented the percentage or the number of words read or spelled correctly.

2.2.2. Phonological Measure

To assess phonological processing abilities, we adimintsered Welte's (1981) Mottier Test. In this test, children were asked to repeat pseudowords. Moreover, children were asked to read aloud a list of 50 pseudowords varying in complexity as a measurement for phonological decoding skills (Paul *et al.,* 2006). A phonetic dictation test (Lauteres Diktat Test) developed by Findeisen & Melenk (1991) was administered to measure children's phonological encoding abilities. In this test, children were asked to spell out words. Only phonetic errors were counted as misspellings and other errors as capitalization errors were not counted.

2.2.3. Categorical Perception

A categorical perception has been also included in the test battery to measure the children ability of phoneme identification (Paul et al., 2006). In this task, Syllables differ only in the onset frequencies of the second and third formants ranging in linear steps from the /ba/ endpoint (item1) to the /da/ endpoint (item10). Categorical perception performance is quantified by using the following formula, $f = \sqrt{\Sigma (ai\text{-}b\ i)^2}$, with a representing the number of responses for /ba/ and b the number of responses for /da/. A high index indicates correct identification of phonemes.

2.2.4. General Cognitive ability

To grantee the normal cognitive functioning of the current sample, we assessed the non verbal IQ using the German version of Standard Progressive

Matrices Test (SPM) which was developed by Heller et al. (1998).

3. Study design

The battery of paper and pencil tests for language ability was administered individually during three 45-minute sessions held on three separate days. In a fourth session, MEG was recorded while children were presented with a passive listening task, whereby auditory stimuli were presented through ear tubes 60 dB/SPL over the individual's hearing level. The two phonemes were the fifth and eighth items[1] of the 10-item continuum of synthetic syllables that ranged form /ba/ to /da/, as presented by a male voice. Both syllables were 250 ms long with a 40 ms formant transition (FT) in the onset frequencies period, which distinguished the two syllables. For both syllables the fundamental frequency of formant F0 was 128 Hz with a linear decline to 109 Hz towards the end of the stimulus. The formant frequencies for the vowel /a/ (which was also the same for both syllables) were 770, 1340 and 2400 Hz for F1, F2 and F3, respectively. Starting frequencies for the formants F2 and F3 were 1365 and 2337 Hz for /ba/, 1567 and 2515 Hz for /da/. Therefore, the only acoustical difference between the syllables was between formants F2 and F3 within the first 40ms. In an auditory oddball task, the syllable /ba/ was used as standard stimulus, while /da/ served as the deviant stimulus. In total, 500 stimuli were presented with a constant ISI of 500 ms. Occurrence rates were 85% and 15% for /ba/ and /da/, respectively. Stimuli were presented pseudo-randomly.

3.1. Data Acquisition

Using a 148-channel whole-head neuromagnetometer (MAGNES™ WH2500, 4D Neuroimaging, San Diego, USA), MEG was measured with the subject in a supine position. A video camera was used to monitor the subject's behaviour and to ensure compliance throughout the experiment. Subjects were instructed not to pay any attention to the syllables they heard. To divert the child's attention from the syllables, a silent video was presented onto a white projection field at the ceiling of the shielded room using a video beamer (JVC™, DLA-G11E) and a mirror system. EOG was recorded by two electrodes attached to the left and right outer canthi and electrodes were placed above and below the subject's right eye. In addition, ECG was monitored via two electrodes - one attached to each forearm. EOG and ECG data were acquired using Synamps amplifiers (NEUROSCAN®). Data were recorded using an online high-pass filter of 0.1 Hz and a sampling rate of 508.63 Hz (bandwidth 100Hz). Spatial density of slow waves generators were then identified following the procedure described by Wienbruch (2007).

3.2. Data Analysis

Slow wave generators were identified in a semi-automated procedure. Artifacts were recognized by visual inspection (e.g. eye blinks, muscle activity) and excluded from further analysis. The acquired data were decimated by a factor of 16 (anti-alias filters were applied automatically) and digitally filtered (1.5–4.0) delta. Using defined channel groups (anterior, center, posterior, left, and right), a single equivalent current dipole (ECD) was fitted for each time point in artifact-free segments. The dipole density was estimated for each subject within each voxel of the source volume by calculating the average number of dipoles per time unit in the voxel over artifact free segments and divided by the number of artifact free sampling points, followed by calculating the logarithm. For further analysis this score was z-transformed using the mean and standard deviation of a normative group (Wienbruch, 2007).

[1] Paul *et al.* (2006) have tested if the stimuli that were used in the MEG experiment (the 5th and 8th items from the continuum of synthetic syllables) were too easy to discriminate. Children's categorical perception performance (number of responses to ⁄ ba ⁄ and ⁄ da ⁄, respectively) at these steps. At step 5, control children performed 89% correct while good categorical perceivers performed 79% correct, and poor categorical perceivers performed 67% correct. At step 8, performance was 87%, 73% and 67%, respectively. Control children performed significantly better than the dyslexic group at step 5 and step 8 (Mann–Whitney U-test Z ¼ 3.26, P < 0.01 and Z ¼ 2.62, P < 0.01, respectively). Thus, it appears unlikely that the stimuli were too easy to discriminate for the dyslexic children.

Table 2. Means and standard deviations of Z scores of Delta density in each region.

Group	CLZ	TLZ	PLZ	FRZ	CRZ	TRZ	PRZ	FRZ
Controls								
M	.66	-.21	-.03	-.02	.56	-1.14	-.52	-.05
±SD	.86	1.54	.67	.95	1.07	1.60	.82	.91
Dyslexics with poor CP								
M	.80	-.32	-.24	.10	.58	-2.28	-.75	-.30
±SD	.64	1.25	.76	.77	.76	1.79	.97	.92

Central left zscore(CLZ), temporal left zscore(TLZ), parietal left zscore(PLZ), frontal left zscore(FLZ), Central right zscore(CRZ), temporal right zscore(TRZ), parietal right zscore(PRZ), frontal right zscore(FRZ).

A repeated measure ANOVA was calculated for the densities of slow wave generators collapsed across brain regions, using the general linear model (STATISTICA6). HEMISPHERIC ASYMMETRY (Frontal Left-Frontal Right, Central Left-Central Right, Temporal Left-Temporal-Right, Occipital Left-Occipital Right) served as within factor, while GROUP (Controls and Dyslexic children with poor categorical perception) served as the between subjects' factor. For each region a hemispheric asymmetry coefficient has been calculated by calculating the difference between z scores of both hemispheres (Left- Right).

4. Results

4.1. Hemispheric Asymmetry and Delta Activity

Analysis of Hemispheric Asymmetry coefficient z-scores of Delta data showed a significant effect for the REGIONAL HEMISPHERIC ASYMMETRY (F (3, 93) =19.5, p<0.01 and an interaction effect of the REGIONAL HEMISPHERIC ASYMMETRY x GROUP (F (3, 93) =4.98, p<0.01). Newman-Keuls Post hoc- analyses revealed that the differential group asymmetries were mainly produced by the temporal region (Newman-Keuls p=0.01). No significant differences between the groups were found for frontal, central or occipital asymmetry (for all p>0.8) (see Figure 2).

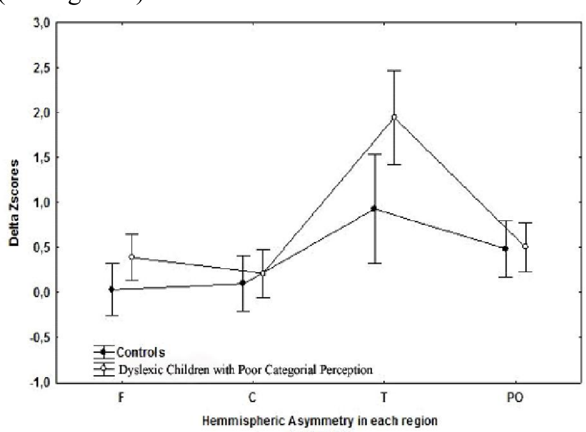

Figure 2- Hemispheric asymmetry in each region. Means of delta z scores (n=33) as a function of the hemispheric asymmetry in each region. Vertical bars indicate confidence intervals at 95%.

4.2. Voxel-based Analysis for the Delta Band.

Localization of abnormal oscillatory responses at the voxel level indicated enhanced slow wave activity over the left hemispheric speech related per-Sylvian regions for dyslexic children with poor categorical perception as compared to average readers as illustrated in Figure 3.

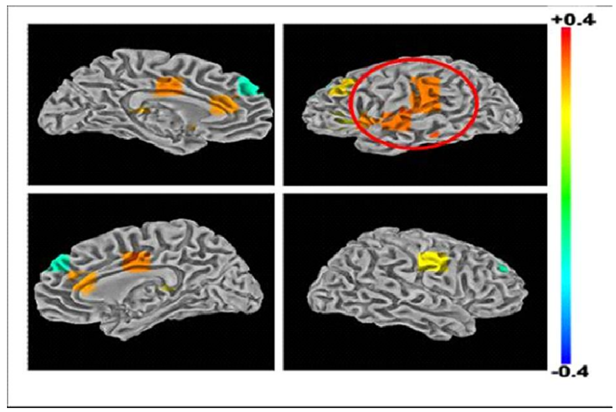

Figure 3- Voxel – based analysis

Differences of z-transformed logarithm voxel-based generator density of slow waves for the left and right hemisphere, medial (top) and lateral (bottom) view. Only voxels with a significance value of t >3.42, p< 0.05 are marked in color. Orange voxels indicate more focal slow waves in children with dyslexia than in the controls. Blue voxels indicate less focal slow waves in children with dyslexia than in controls.

5. Discussion

Using magnetic source imaging, the present exploration of abnormal slow waves in dyslexic children with poor categorical perception confirms and extends previous findings based on EEG-analyses (e.g., Penolazzi *et al.,* 2008). The major finding of this study was an elevated delta activation localized in voxels of the left per-Sylvian regions in dyslexics with categorical perception as compared to controls. These results are consistent with a series of previous neuroimaging studies, which have converged to suggest an atypical organization in the temporal cortex of the left-hemisphere for dyslexia, suggesting a reduced engagement of the per-Sylvian regions for phonological processing, altered white-matter connectivity, and functional plasticity associated with effective intervention (Gabrieli, 2009). Moreover, this finding has been in line with the assumptions of Merzenich and his colleagues (1993) that insufficiently developed or degraded representational maps are centered in cortical per-Sylvian areas leads to noisier processing, which then would demand more time to correct the recognition of phonemes, and words, accordingly.

Recently, it has been suggested that the two hemispheres are functionally segregated in terms of processing the temporal and spectral features of an auditory input. As a result, it is strongly plausible to assume, here, that segmentation and integration of sounds also rely on lateralized modules. Previous imaging studies showed that speech processing at the initial stages produced bilateral activation, at least at the level of the auditory core and surrounding superior temporal gyrus as assessed by hemodynamic and electrophysiological methods (In: Poeppel, 2003). Importantly, our current results are consistent with studies that examined segregation and functional hemispheric lateralization in the auditory cortex suggesting that the left hemisphere is optimized for temporal processing, while the right one seems to be tuned for syllabic/prosodic processing (Guiard *et al.,* 2000; Hall *et al.,* 2002; Zatorre, 2003; Zatorre & Belin, 2001; Hickok& Peoppel, 2000; Peoppel, 2001; 2003). Zatorre and Belin (2001) , for example, not only showed left hemispheric dominance during temporal and right hemispheric dominance during spectral auditory processing, but they also suggested that hemispheric lateralization might partly originates from early basic neural processing levels dealing with the spectral and temporal features of auditory inputs. Recent evidence for this view has been derived by Okamoto et al.'s observations (2009).of different neural responses elicited by change in spectral versus temporal stimulus between the two hemispheres. To illustrate, results showed that N1m responses evoked by the spectral stimulus change were comparably larger in the right hemisphere, whereas the N1m responses evoked by the temporal stimulus change were larger in the left. Significantly, the authors concluded that hemispheric laterality of neural responses does not depend on a specific sound type but rather on spectral and temporal variances, which are differentially encoded into neural activity in the cochlea. Therefore, they strongly suggested that hemispheric lateralization for auditory processing is not only limited to sounds conveying meaning, but also is extended to non-speech signals (e.g., music)

Noteworthy, the current observation of differences in the oscillatory properties between children with poor categorical perception and controls supports the notion of hemispheric specialisation. The fact that the slow waves differentiate both dyslexic children with poor categorical perception and controls suggests differences in the lateralisation of the processing of the temporal and spectral properties of the auditory input, namely CV syllables. If we assume with Poeppel *et al.* (2008) that the spectral versus temporal right-left asymmetry is a consequence of the size of the temporal integration windows of the neuronal ensembles in these areas, then we would expect to see lateralised differences in the frequency of brain waves, consistent with the present observation. Given that neuronal ensembles in the left temporal cortex are associated with a 20-50 ms shorter integration, the left hemisphere cortical fields preferentially reflect temporal properties of acoustic signals such as "fast frequency changes." The right hemisphere cortex houses neuronal ensembles that occur at longer (150-300 ms) integration windows, and therefore are better suited to analyze spectral changes. The deviant hemispheric lateralisation of delta activity in dyslectic children with categorical perception suggest that the left hemisphere participates in the temporal rather than spectral processing. However, it remains to be tested if this type of hemispheric lateralisation is better suited for other tasks that rely more on the examination of the binaural spectral properties, such as the spatial localisation of sounds.

6. Conclusions

Overall, the findings of the current study point to several different physiological and functional differences between dyslexic children with poor categorical perception and controls specifically in regards to impairments of the sub-lexical phonological representation level that are related to altered laterality patterns of focal slow brain waves in temporal regions, as measured by MEG. Compared to controls, the present data showed that dyslexic children with poor categorical perception are marked by the following: (a) a deviant hemispheric specialization in the region of the temporal lobe, (b) enhanced delta activity in the left per-Sylvian regions; and c) malfunction of the left hemisphere to process temporal features of the auditory input, namely phonemes.

In conclusion, these observations strongly support the hypothesis that while the left hemisphere of the human auditory cortex of has superior temporal resolution capabilities, the right hemisphere has better syllabic resolution capabilities. Therefore, we suggest that this results in a failure to segregate speech sounds, making it more likely that dyslexic children with poor categorical percption have insufficiently developed or degraded representational maps. This subsequently results in noisier processing which then would require more time for correct recognition of phonemes and consequently words (Merzeinch et al., 1993).

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