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The role of phonological awareness, speech perception, and auditory temporal processing for dyslexia

Abstract There is strong evidence that auditory processing plays a major role in the etiology of dyslexia. Auditory temporal processing of non-speech stimuli, speech perception, and phonological awareness have been shown to be influential in reading and spelling development. However, the relationship between these variables remains unclear. In order to analyze the influence of these three auditory processing levels on spelling, 19 dyslexic and 15 control children were examined. Significant group differences were found for all speech variables, but not for any non-speech variable. Structural equation modeling resulted in a fairly simple model with direct paths to the respective next lower level. One additional path from preattentive speech processing to spelling had to be included in order to improve the model fit. These results strengthen the role of speech and phonological processing for the etiology in dyslexia.

Key words Dyslexia – phonological awareness – mismatch negativity – speech perception – auditory temporal processing

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Introduction

During the last two decades a number of encouraging discoveries have been made about importance of early linguistic abilities for reading and spelling development (10, 41). In particular, many studies have demonstrated the importance of early sensitivity to the phonological structure of words (16, 25). Phonological awareness, i.e., the ability to identify and manipulate phoneme-sized elements of spoken language is strongly related to early reading acquisition. In fact, phonological abilities are stronger predictors than such important correlates as intelligence, vocabulary, and listening comprehension, and remain significant predictor of reading achievement even after such factors as intelligence and verbal ability are partialled out (15). However, it should be acknowledged that the relationship between reading and phonological awareness is a reciprocal one; while phonological awareness is prerequisite for normal reading, reading experience also facilitates phonological awareness (23, 28). The importance of phonological awareness for reading and spelling was demonstrated in several studies:

- *Correlational studies:* Phonological awareness in pre-school years is a significant predictor of later success in reading and spelling development. This has been found in different cultures and in many languages (3, 8, 16, 18, 25, 41).

- *Training studies:* Training studies have provided evidence that pre-school children can benefit from early language games that direct their attention to phonemes (3, 4, 19, 33).
- *Studies with adults:* Adult dyslexics are less phonologically aware (35) even than younger normal readers of similar reading ability (6) and even compensated adults (dyslexics who have attained a fluent reading ability through remedial teaching) have a phonological awareness deficit (27).
- *Twin studies:* Heritability for phonological awareness is high ($h_g^2 = 0.60$, 26).
- *Linkage studies:* Linkage with chromosome 6 markers and phonological awareness subtype (11, 12, 14).
- *Brain imaging studies:* Reduced activation of mid- to posterior temporal cortex in dyslexics during a phonological processing task (32).

Furthermore, for all phonological processing tasks speech perception might be a prerequisite condition (37). The typical speech perception task is to identify stimuli from a continuum of synthetic sounds which range smoothly from one end point (e.g., /ba/) to another (e.g., /da/) (20). Most of this research involves perception of syllables beginning with stop consonants (7, 13, 20). These sounds may be relatively difficult to perceive for at least two reasons. First, they occur quickly in time, as compared to other consonants. Second, unlike some other speech sounds such as vowels, their creation involves the transition of different voice frequencies (17). Most past studies have found speech perception deficits in reading-disabled children and adults though some have not (7, 13, 20, 22). The procedures in these studies were stimulus identification and discrimination which required subjects to focus their attention on the relevant stimulus dimension, especially if stimuli were masked by amplitude-matched noise (5).

The question arises whether the speech perception deficit of the dyslexics already occurs on the level of sensory perception which is characterized by preattentive and automatic processing. A neurophysiological paradigm which is best suited to examine pre-attentive and automatic central auditory processing is the mismatch negativity (MMN) (24). The MMN is a negative component of the event related potential (ERP), elicited when any discriminable change occurs in a sequence of repetitive homogeneous auditory stimuli (24). The MMN occurs approximately 100 to 300ms post-stimulus onset and is elicited by changes in frequency, intensity, or duration of tone stimuli, or changes in complex stimuli such as phonetic ones and usually reaches its amplitude maximum over fronto-central scalp. The MMN is assumed to be a result of a mechanism that compares each current auditory input with a trace of recent auditory input stored in the auditory memory (24).

As shown by the works of Tallal (39, 40) and Reed (31) there is another level of auditory processing relevant for speech perception and phonological processing which is called temporal processing. Temporal processing refers to the ability to perceive stimuli which are presented in very rapid succession as different. Tallal found a temporal processing deficit for dyslexic children (40). In this study Tallal used non-speech stimuli which were presented with different interstimulus-intervals. The temporal processing deficit was only present when the stimuli pairs were presented at short interstimulus-interval (ISI < 305 ms). The correlations between auditory temporal processing and phonological decoding ($r = 0.81$) as well as with word knowledge ($r = 0.64$) and spelling ($r = 0.67$) were high.

All these findings raise the question, how are the various linguistic and “pre-linguistic” abilities related to each other and to reading and spelling? Is there a fundamental factor, a general auditory processing factor, underlying all the other language skills? Or do two or more basic processes contribute independently to reading and spelling?

We propose a four level model of auditory and phonological processing that could be an adequate approach for understanding the different auditory processing and linguistic deficits described for reading and spelling disability (Fig. 1).

We assume that pre-attentive and automatic processing of auditory stimuli is a prerequisite for active speech perception which will by itself directly influence phonological awareness. Phonological processing refers to the most complex hierarchical level in linguistic processing which directly influences reading and spelling abilities. These four levels of linguistic abilities may represent a pathway from basic auditory processing to higher cognitive functions like reading and spelling.

The objectives of our studies were to investigate the interdependence of different auditory processing levels, e.g., auditory temporal processing, passive and active speech perception, and phonological awareness. First we examined whether spelling disabled children are impaired regarding different pre-attentive and attentive cognitive processing abilities. Second, in order to investigate the interdependence of different auditory processing levels we calculated correlations between these variables. Third to investigate the influence of these components on spelling ability we calculated a structural equation model.

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Fig. 1 Hierarchical model of different auditory processing levels in reading and spelling development

	Processing level	Paradigm and Measures
Level 1	Pre-attentive and automatic processing of auditory stimuli	Passive oddball paradigm, mismatch negativity
Level 2	Conscious processing of auditory stimuli	Gap detection. Tone and speech discrimination
Level 3	Conscious and cognitive (phonological) processing	Phonological awareness: phoneme counting
Level 4	Spelling and reading	Writing to dictation, word reading

Subjects and Methods

Sample

19 spelling disabled (mean age 12.5 ± 0.3) and 15 control children (mean age 12.6 ± 0.8) at grades 5 and 6 were assessed (only boys). Both groups did not differ regarding their IQs (IQ of spelling disabled was 104.0 ± 11.0; IQ of controls was 104.6 ± 12.3). The spelling disabled children visited the same high school as the control children and were ascertained through a special boarding school for dyslexics. Inclusionary criteria were to be a native monolingual speaker of German, no middle-ear infection within the week of testing, no hearing problems and no uncorrected visual acuity, no apparent neurological, emotional or behavioral deficits or unusual educational circumstances that could account for poor reading and spelling ability. Spelling disability was assumed if there was a discrepancy of at least 1 standard deviation between actual spelling ability and expected spelling based on IQ (34). Additionally, the spelling disabled group had a significantly lower word decoding ability in comparison to the controls ($p = 0.01$). All subjects had normal hearing and reported themselves to be strongly right-handed according to a handedness questionnaire (37).

Measures Gap detection

The bursts were synthesized from sine waves with frequencies from 1 Hz to 2000 Hz, amplitude and phase randomly distributed. The duration of the stimuli was 400 ms plus the gap. The auditory stimuli were presented binaurally by insert earphones. The inter-signal-interval (gap) between the bursts was varied according to the accuracy of the subjects' latest responses (adaptive testing). The starting gap was 80 ms, after two successive correct responses, the gap was decreased, given one incorrect response the gap was increased by one step. The step size was varied in 10 ms steps from 80 ms down to 50 ms gap duration, then in 5 ms steps from 50–20 ms gap duration then in 1 ms steps from 20–0 ms gap duration. The subjects were told to press the left mouse button if they heard one noise (i.e., no gap), and to press the right mouse button if they heard two noises (i.e., a gap).

Passive speech and tone perception

The aim of this study was to determine the relationship between dyslexia and central auditory processing. To examine whether the speech perception deficits of dyslexics are pre-attentive and automatic, we used a passive oddball paradigm which requires the subjects to focus their attention on a different sensory modality (i.e., watching a silent movie) than that of the test stimuli. To elicit an MMN we used speech stimuli as well as tone stimuli. The tone stimuli serve as a control condition to examine whether the central auditory perception dysfunction is specific for speech stimuli.

Acoustical stimuli were produced by 90 ms of 1000 Hz ('standard' $p = 0.85$) and 1050 Hz ('deviant' $p = 0.15$) sine waves and were presented in a pseudo-random order (at least five standards between two deviants) with a constant ISI of 590 ms (from onset to onset). Speech stimuli (standard /da/- deviant /ba/), were synthesized with the Computerized Speech Research Environment (9).

To control for level of arousal and to minimize subjects' attention to the stimuli, they were told to watch videotaped silent movies and to ignore the test stimuli. Subjects were instructed to follow the screen play and to answer several questions on topics of the movies after the EEG recording. Electrodes were placed at 19 scalp sites based on the International 10-20 System: Fp1, Fp2, F7, F8, F3, F4, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, O2 (referred to linked ears, ground electrode at Fpz). Eye movements and blinks were monitored by two electrodes placed below the subjects' right and left eyes and the Fp1 and Fp2 electrodes. The EEG was amplified with Schwarzer amplifiers, time constant 0.6 s; upper frequency cut-off at 85 Hz. The EEG was recorded continuously and A/D converted at a sampling rate of 172 Hz. The signals were averaged into epochs of 750 ms, including a prestimulus baseline of 50 ms. Difference waveforms were calculated by subtracting ERPs to standards from those to deviants.

Speech and tone discrimination

The same speech and tone stimuli were used as for measuring MMN. Subjects had to identify a /ba/ or 1000 Hz stimulus by pressing the left button of a computer mouse, /da/ or 1050 Hz stimulus by pressing the right button.

Phoneme counting

Subjects were instructed to count the phonemes of 8 nouns which were selected from the most frequently used words in German primary school (29). Three nouns consisted of three, 2 of four and three of five phonemes.

Intelligence

Intelligence was measured with a German adaptation of the Culture Fair Intelligence Test, Scale 2 (42).

Spelling

Spelling ability was measured by a grade-appropriate German spelling test (writing to dictation) for the children (30).

Word Reading

The reading list for the children comprised 30 nouns selected from the most frequently used words in German primary school (29). Thirty words were selected for the word item list, five consisted of two syllables, 10 consisted of three syllables and 15 consisted of four syllables. These words were all nouns.

Results

Regarding the individual gap detection thresholds, we calculated group means in order to examine the relationship between the gap threshold and spelling ability (Table 1).

For statistical analyses of the electrophysiological data, the areas of the electrodes of the fronto-central region (F3, Fz, F4, Fp1, Fp2, C3, Cz, C4) were averaged. Fz as the assumed center was given double weight. The resulting mean value was used to examine group differences.

We calculated a MANOVA in order to test for group differences regarding the assessed variables. Table 1

Table 1 Means ± standard deviations and univariate p-values of the group comparisons

	Controls (n = 15)	Spelling disabled (n = 19)	p-value (univariate)
Gap detection	9.4 ± 4.7	14.1 ± 10.3	0.12
MMN tones	–416.6 ± 528.9	–466.5 ± 410.7	0.55
Tone discrimination	37.5 ± 13.2	30.4 ± 42.2	0.085
MMN speech	–554.8 ± 536.2	–112.3 ± 291.5	0.007
Speech discrimination	42.2 ± 7.1	32.4 ± 32.4	0.045
Phoneme counting	4.8 ± 2.1	2.4 ± 1.5	0.0009

Table 2 Correlation coefficients between the different processing levels[1]

	Speech discrimination	Phoneme counting	Spelling	Word reading
MMN (speech)	**0.34**	0.29	**0.36**	0.11
Speech discrimination		0.32	**0.35**	0.18
Phoneme counting			**0.55**	–0.14

[1] Significant coefficients are printed **bold**. The sign of the MMN variable has been altered in order to avoid confusion because of sign changes.

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shows means, standard deviations, and univariate p values. The multivariate p-value is 0.0038.

The multivariate p-value proves the overall influence of tone and speech variables; however, the univariate p-values of Table 1 show that the tone variables (gap detection, tone MMN, and tone discrimination) do not contribute to the significant group effect. Therefore, further analyses were restricted to the speech variables.

The main purpose of this study was to analyze the relations between the different levels of auditory processing (Fig. 1). The correlations between word reading and the different speech variables was considerably low (Table 2), thus the analyses were focused on spelling ability. Table 2 shows correlations among these variables and spelling.

Except for two pairs of variables, all coefficients between spelling and linguistic variables are significant. In order to analyze the relations of these variables in depth, we calculated a structural equation model (LISREL) according to the theoretical model shown in Fig. 1.

Paths other than those directly connecting neighboring levels were suppressed. This means that 3 out of 6 possible paths were used in the model. The resulting model fit (Adjusted GFI) was 0.74, p_{Chi^2} was 0.095. These measures indicate that the model does not adequately fit the data. Thus, in the next step another path (MMN → Spelling) was introduced. This path was chosen because it had the highest coefficient of the remaining 3 in the saturated model with all paths.

Goodness of Fit index of this model was 0.97, adjusted Goodness of Fit index was 0.88, $p_{Chi^2} = 0.30$. 42% of the spelling variance could be explained in the model.

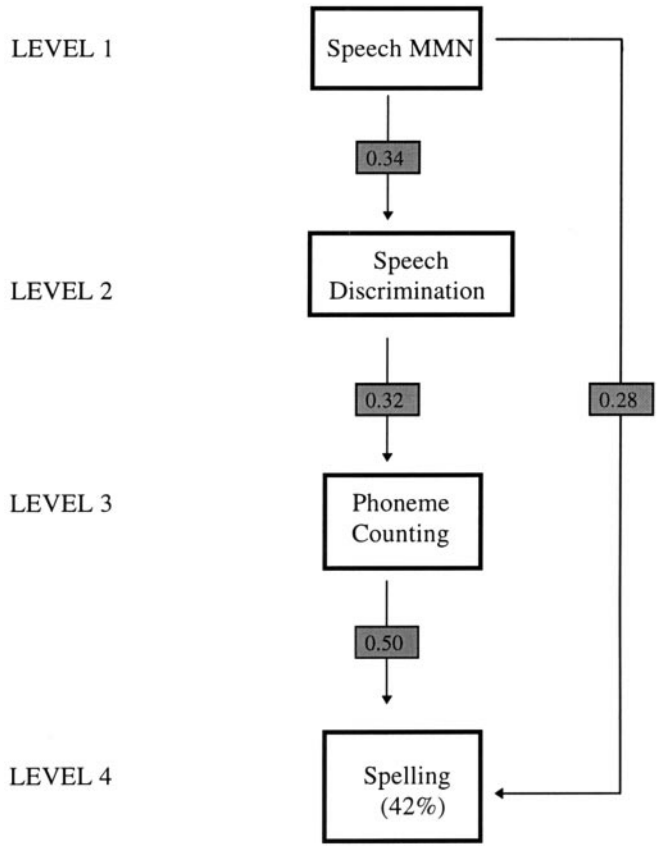

Fig. 2 LISREL Model

Discussion

We examined different pre-attentive and attentive/cognitive levels in dyslexics and controls.

First, we found that from the assessed variables, none of the non-speech variables differentiated the groups of dyslexics vs. controls significantly. The findings that dyslexics perform on tasks requiring passive discrimination of simple tones (MMN) as well as controls did not support a low level auditory processing deficit in dyslexia (37). Recently, Baldeweg et al. found a reduced amplitude of the frequency MMN in dyslexics, suggesting a sensory deficit in processing the frequency of incoming sound (1). However, we did not find an attenuated frequency MMN in dyslexic adults (38). Thus it remains controversial whether dyslexics are characterized by a pre-attentive auditory processing deficit of non-speech stimuli.

In this study no evidence was found for an auditory temporal processing deficit using a gap detection paradigm. We also found this in an independent adult sample in a previous work (36). These results suggest that the processing of rapidly presented non-speech stimuli is of minor importance for spelling ability.

Second, the groups in our study differed regarding all of the speech variables. This points to a specific deficit regarding auditory speech stimuli. The variables chosen for the evaluation of our 4 level model are intercorrelated, which proves that the different levels of processing of speech stimuli are closely connected. The LISREL analysis pointed out that the underlying structure is fairly simple. Our assumption of a direct influence of each level on the respective lower next level could be confirmed. This means that there is a direct pathway from passive speech perception to active speech perception to phoneme counting to spelling. The relationship between speech discrimination and phonological awareness has been investigated by McBride-Chang (21). She found that the influence of speech perception on reading ability is mediated by phonological awareness. In this study, we found evidence that for spelling the influence of speech discrimination is mediated by phonological awareness as well.

Deficits in speech perception, especially the differentiation of phonemes like /da/- /ba/ have been shown to be confounded with reading and spelling deficits (7, 10). However, this paradigm requires children to actively discriminate phonemes. This cognitive process could be influenced by the level of attention, by motivation and by memory span performance. Thus it remains unclear whether the deficits found in speech perception point to an underlying deficit of dyslexia, or are just a side-effect, or are like dyslexia caused by the same underlying, yet unknown, deficit. The great advantage of MMN by means of a passive oddball paradigm is that it examines a very early process, and thus allows conclusions about the cause of dyslexia, rather than just finding coinciding deficits. Furthermore, the MMN is generally considered pre-attentive (24), and thus also rules out lack of attention and/or motivation as cause of poor performance. Our results therefore suggest that the deficits in pre-attentive speech processing can be considered a cause of dyslexia. Therefore, this measure could define a promising candidate phenotype for quantitative trait analysis in genetics of dyslexia (see 43 in this volume).

This is the first study which simultaneously examined the importance of several different auditory processing levels on spelling ability. Although our sample is rather small and represents just a small range of age, our results can give some answers of regarding the role of linguistic factors for spelling. However, only 42% of the spelling variance could be explained suggesting that other factors, probably visual processing and orthographic abilities, are also relevant for spelling.

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