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Number-word reading as challenging task in dyslexia? An ERP study

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Abstract

The aim of the present study was to evaluate processes of lexical access, selection and early semantic access in young native Hungarian students as well as in dyslexics compensating successfully for their reading problems of developmental origin. The present study made use of the well-known lexical decision paradigm in which event-related potentials (ERPs) elicited by words, number-words and pseudowords were measured. Subjects had to judge whether the letter strings seen were meaningful or meaningless. Our results suggest that in good readers additional activity occurs in the sensory or selection stage of lexical access when words of low sight frequency, e.g. number-words are read. Significant processing differences for words vs. number-words were found in the later stage of processing. Based on our ERP data we do not suggest number-words for judging general features of lexical processing, especially when developmental dyslexia is the focus of study. Our results show that young adults may develop a particular compensation strategy for reading words of different frequency. We found that: (1) Lexical access is fast and accurate in good readers and the early components elicited by words and number-words do not differ. (2) Attentional effort is reflected by enhanced early components to number-words. (3) Dyslexics may compensate for the weakness of sight word vocabulary, characteristic for frequent words as well, during lexical selection and at a later stage of processing. (4) Dyslexic adults, who compensate well for reading difficulties, differ significantly in this later stage when words have to be read. (5) The late positive component of ERPs reflects additional activation allocated to word reading when low frequency words such as number-words are read. Good readers show this effect as well, therefore, the largest difference found between dyslexics and controls is found for frequent words. (6) The early semantic access is absent in dyslexics when pseudowords are read and this process may be one of the strategies used by dyslexics in a transparent orthography.

Keywords: Lexical decision; Word and number-word reading; Event-related potential (ERP); Early components; Late positive component (LPC); Dyslexia; Compensation

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1. Introduction

In the last decade different theories of reading disability have been proposed, based on putative deficiencies of several types of processing: the visual system; the acoustic system; and the language system. However, there is a general consensus among dyslexia researchers that whatever the contribution of various systems and processes may be, one of the core difficulties occurs within the language system, especially at the level of phonology. A well functioning phonological representation, based on normally developed phonemic awareness in childhood, seems to be crucial in reading acquisition.

There is overwhelming evidence that a deficient phonological awareness (PA) is characteristic of the reading disabled (RD) and PA tasks consistently separate RD children and children without reading problems. Moreover, experimental evidence shows that phonological processing deficits persist into adulthood (Bruck, 1992; Shaywitz et al., 1999). Phonological processing is often studied by using different measurements of brain activity where the decoding process is stressed by word vs. pseudoword reading tasks.

There are two principal ways for encoding orthography into phonology; the first involves direct connections between orthography and phonology, the second is indirect, translating familiar words into phonology via semantics. The two principal ways involve different processing stages as well as different concerted actions of the contributing brain areas. A large number of experiments have demonstrated that identification of printed words implicates a posterior cortical reading system consisting of ventral and dorsal components. The ventral circuit, including the lateral extrastriate areas as well as the left inferior occipito–temporal area, is the one that shows a robust activation in word-reading tasks as revealed by many neuroimaging studies (e.g. Fiez et al., 1999; Pugh et al., 2000). As shown by electrophysiological studies, the ventral circuit is the source of early lexicality effects, and may be responsible for the temporal dissociation in processing words and non-words.

The temporo–parietal circuit has long been classified as one of the problematic areas contributing to reading difficulties. The angular gyrus is considered especially relevant in mapping print onto phonology. Experimental findings of functional imaging studies revealed abnormal activation of the temporo–parietal circuit during reading-related tasks, as well as in other types of linguistic analysis in reading disabled subjects (Gross-Glenn et al., 1991; Pugh et al., 2000; Rumsey et al., 1999; Shaywitz et al., 1998).

As shown by the neuroimaging studies, several differences can be found between processing characteristics of the temporo–parietal and occipito–temporal circuits of the left hemisphere. One of the most critical features of the two systems is their apparently distinctive role in word and non-word reading. While the temporo–parietal circuit is associated with slow, attentive, rule-based analysis of printed words, the occipito–temporal circuit is mainly involved in a nearly automatic, less attention-dependent word recognition (Pugh et al., 2001; Shaywitz et al., 2002). Based on recent neuroimaging data one may assume that this fast orthographic processing heavily relies on repeated experience of printed words bound into highly integrated representations called sight word vocabulary.

The distinct role as well as the different developmental course of the dorsal and ventral circuits is supported by experimental data. In skilled readers, the dorsal circuit responds with higher activity to pseudo-words and low frequency words, while the ventral circuit produces higher activity to familiar words (Tagamets et al., 2000; Frackowiak et al., 1997). The ventral system is involved in word recognition, as shown by its higher activity of well learned, mainly high frequency words (Brunswick et al., 1999). Moreover, simple word identification makes a higher demand on ventral than on dorsal sites (Brunswick et al., 1999), while phonological analysis strongly relies on the dorsal processes (Pugh et al., 2000; Shaywitz et al., 1998). However, in successfully performed reading tasks the two circuits should work in concerted action as shown by event-related magnetic responses reported by Salmelin and her coworkers (Salmelin et al., 1996; Tarkiainen et al., 1999). As demonstrated by the Finnish group, the brain activity to linguistic and to non-linguistic stimuli is different in the occipito–temporal area as early as 150–180 ms and further processing of the stimuli is done 100 ms later by the temporo–parietal area. However, the early ventral response is not seen in adult developmental dyslexics. Moreover, recent studies in dyslexic children revealed anomalous activation both in dorsal and ventral sites during word and pseudoword reading tasks (Shaywitz et al., 2002). Recent results (e.g. Pugh et al., 2000) are consistent with the specific phonological deficit hypothesis, showing that processing deficits of the left posterior system are evident when orthography to phonology translation is required. Moreover, homologous right posterior areas may function as compensatory circuits in dyslexic readers (Paulesu et al., 2001; Simos et al., 2002).

It is well known that left parietal dysfunctions may contribute to processing abnormalities in dyslexics when attention demanding, rule-based analysis is required in a reading task. Moreover, further difficulties have to be taken into account when the right parietal involvement shown in normal adults (Mayall et al., 2001), is also disturbed.

The right parietal lobe dysfunction hypothesis was suggested by Hari and Renvall (2001). According to the authors, one of the core deficits in dyslexia is a problem with attention triggering and shifting due to processing disturbances in the right parietal lobe. Low-level visual and acoustic stimuli were presented at a fast rate, producing brain activity patterns similar to that of neglect patients. Therefore, the authors called the pattern found in dyslexics mini-neglect. Recent ERP data of Wimmer et al. (2002) are in accordance with the Hari and Renvall (2001) model. Wimmer et al. analyzed the N1 of visual ERPs elicited by number-words and pseudowords (composed by syllable change in the number-words used) recorded over the frontal, frontocentral and centroparietal sites in 11-year-old boys. Poor readers showed lower amplitude N1 to pseudowords at the right central electrodes as well as at two left frontal sites, F3 and FC5, which the authors argued was consistent with an attention deficit. Unfortunately, they did not discuss fully the additional N1 activity to pseudowords (shown in Fig. 2) present only in poor readers. The authors focused on similarities with the Hari and Renvall findings and seemed to neglect the strikingly different, highly symmetric N1 distribution to pseudowords in poor readers. Wimmer et al. further introduced an interesting hypothesis about visual input reduction in processing pseudowords as a deliberate strategy used by poor readers. They assumed that poor readers need to limit their attention to a small number of letters when confronted with pseudowords and this is reflected by a reduced N1 occurring within a time window of 50–150 ms.

Traditionally, word recognition is considered to take place in two consecutive steps, lexical (word-form) access and semantic access. While lexical access involves sensory processing of the word form, semantic access activates the related concept. Lexical access occurs within 200 ms, where the first step, the sensory processing of the word form, is reflected by the N100 and the second step that distinguishes between perceptually similar words and non-words, is assumed to be shown by the next ERP component peaking approximately 200 ms. Both steps of lexical processing may be affected in poor readers, therefore, a particular paradigm (e.g. that used by Wimmer et al. (2002)), gives information about only one special class of words. A more complex view is provided by a recent review by Hinijosa et al. (2001). The authors propose that a particular ERP component called recognition potential (RP) may reflect an additional process that of lexical selection. The RP described by Rudell (1991) is a left lateralized negativity peaking at approximately 200 ms, most probably emanating from the fusiform gyrus, whose amplitude increases when ‘wordness’ of the stimuli presented increases (Martín-Loeches et al., 1999). The possible role of the fusiform gyrus in generating the RP gives rise to furthermore speculation about the distinct steps of lexical processing if we take into account that this area responds with increased activation to orthographically regular letter sequences, regardless of whether the lexemes presented are real or not (Cohen et al., 2000).

Taking all the relevant ERP studies together, our hypothesis is that sensory processing stages of the lexical access are reflected by the ERP components present in the first 200 ms after stimulus onset, whereas lexical selection and early semantic access is reflected by the occurrence and changes of the later components. The recognition potential sensitive to the semantic category of the stimulus (Martín-Loeches et al., 2001), seems to be one of the candidates for studying the early word-level semantic access.

The aim of the present study was to evaluate this three-phase process of lexical access, selection and early semantic access in normal reading native Hungarians. Transparent orthography is one of the main characteristics of the Hungarian writing system, therefore, no differences are present in the regularity of letter sequences. That means pseudowords can be easily read because no particular rules are required for translating orthography into phonology. The possible anomalies as well as compensation strategies used by adults were also analyzed in poor readers with history of developmental dyslexia. Our hypotheses were that: (1) The lexical access is fast and accurate in good readers and differences between reading words and pseudowords may be found in the early processing stage, reflected by the N100 component. (2) If sight word vocabulary plays a particular role in lexical access, changes due to attentional effort would be shown by the early ERP components to number-words as compared to words characterized by regular letter sequences. (3) If number-words require further processing, that is early semantic access, late ERP components should also show differences in comparison to words. (4) Dyslexia-related processing anomalies may occur early and the deficit of sensory processing of the word form should be reflected by a low amplitude N100. (5) In dyslexics, the compensation for deficient access may occur in the second step of the lexical access and would be shown by an increased amplitude in the ERP component at approximately 200 ms, i.e. the RP. (6) A strategic reduction of attention to pseudowords (suggested by Wimmer et al.) would cancel furthermore processing, therefore, the second step of lexical selection and early semantic access would be missing, reflected by an absent RP or any further late component. (7) If sight word vocabulary has been weakly defined in dyslexics, ERPs to words and number-words would not differ.

The present study made use of the well-known lexical decision paradigm in which participants are asked to read words and pseudowords and judge whether the letter string seen is meaningful or meaningless. Although frequent words were chosen as meaningful lexemes, a rarely used semantic difference was introduced, that is lexical decision was required for words vs. pseudowords and number-words vs. pseudowords. We assumed, that reading number-words might differ from that of words (nouns) for two reasons. First, numbers have a different external representation, namely digits; second, number-words should have a weaker representation in the sight word vocabulary than other words, especially frequently used nouns. The stimulus material used was orthographically regular. This requirement was easily fulfilled as Hungarian had a shallow orthography, root words represent a nearly one-to-one letter-sound rule and inconsistencies due to morphophonemic variations were excluded.

2. Methods and materials

2.1. Subjects

Subjects were 12 right-handed university students (six males and six females) between 19 and 22 years of age. Data of three right-handed university students (18-, 19- and 20-year-old males) with severe reading problems of developmental origin are also reported as additional case studies. All subjects were recruited for psychophysiological experiments by a ‘job help’ student organization. The three students reporting on reading difficulties from their childhood on were separated from the good readers’ group and were included in the case reports. Records of dyslexia were traced back with the help of their school therapist. Their reading ability was normal for accuracy (only few or no errors in the Hungarian reading test developed for adults by our research group) and 1.5 S.D. below normal for speed. All subjects investigated had normal or corrected to normal vision, and provided informed consent.

2.2. Design and procedure

Subjects were sitting in a comfortable chair (placed in a sound-attenuated and electrically shielded room) in front of a 19-inch computer screen. Words of two types and pseudowords (black letters on a light green background) were presented in the center of screen, 1 m in front of the subject. Each word was printed in lowercase and presented for 1500 ms. Words (W) and pseudowords (PsW1) as well as number-words (NW) and pseudowords (PsW2) were presented in consecutive experimental blocks. In each condition, 80 stimuli of each type were presented with equal probability. In the word condition (condition W), the subjects had to judge whether the letter string seen (W or PsW1) was a meaningful word or not. In the number-word condition (condition NW), the lexical decision had to be made between the written name of digits and pseudowords (NW or PsW2). The two different experimental blocks were repeated twice, the blocks were given in random order. In an experimental session four series, two of each condition was given.

The subjects' task was to push a green button of a three-button device when the letter string seen formed a meaningful word and a red one when the letter string was meaningless. In order to keep the subjects' attention focused as well as to establish a better signal-to-noise ratio, self-initiated trials were used. Every trial started with the presentation of a fixation cross and the subjects could start a trial by pressing a button with the right thumb. A self-initiated trial started with a 1000 ms pre-stimulus time followed by a letter string presented for 1500 ms. Errors and reaction times (RT) were monitored and recorded. Subjects saw their performance scores (hits and errors) after the session. Standard instructions were given before the experiment, telling subjects that their task was to press one of the response buttons when the letter string occurring on the screen was meaningful and the other one when it was not. No particular instruction was given about the speed required. The experimental design based on self initiated trials provided a good control for accuracy by allowing subjects to refocus their attention after the error trials. Subjects practiced on a different stimulus list before the experimental trials and it was double-checked whether they fully understood the task.

2.3. Recording and data analysis

EEG was recorded via Ag/AgCl electrodes from 18 scalp sites (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, Oz and O2) placed according to the international 10-20 system. Ocular artifacts were monitored by electrodes placed below and above the eyes (orbital ridge) as well as outside of both canthi. Linked ears served as reference and the middle of the forehead as ground. The electrode impedance was kept below 5 kΩ. The EEG was amplified by Neuroscan Synamp amplifiers with a 0.01–70 Hz (half amplitude cutoff) bandpass. The sampling rate was 250 Hz. The offline filter was set to 0.10–30 Hz. All epochs exceeding ± 60 μV on any electrodes were rejected. Approximately 12% of the trials were contaminated with eye movements or muscle artifacts. Stimuli and port codes were delivered by the Neurobehavioral Systems' Presentation program, version 0.47b. Data processing was performed by using the BrainProducts' Brain Vision software package.

Due to the very low error rate (1.5% in good readers, 3% in dyslexics), only averaging of ERPs to hits could be performed. Data epochs extended from -100 to 1000 ms relative to stimulus presentation. Baseline computation was performed in the interval between -100 and 0 ms. Changes of the different ERP components recorded in good readers were analyzed on individual averages, by measuring the maximal and minimum amplitudes as well as the peak latencies in four latency windows (LW). Twelve recording sites were chosen for the statistical analysis; four midline electrodes (Fz, Cz, Pz and Oz) and the corresponding left and right electrodes (F3, F4, C3, C4, P3, P4, O1, O2). The amplitude and latency measures were performed by using Matlab. For statistical analysis the GLM (general linear model) for repeated measures of univariate ANOVA of the Statistica 6.0 software package was used. The ANOVA was conducted with factors of WORDNESS (word, number-word and pseudowords) and

ELECTRODE (12 sites, listed above) as within subject factors. Four latency windows (LW) were used for analysis: 80–140 ms (LW1), 140–200 ms (LW2), 200–400 ms (LW3) and 400–800 ms (LW4). The ANOVA was epsilon corrected by a strict (Greenhouse–Geisser) as well as a somewhat more liberal (Huynh) method. In case of interactions post-hoc tests were also performed (Huynh–Feldt).

Due to the small number of dyslexics, reading ability (dyslexia and control) was not included in the ANOVA. Group averaged ERPs recorded in the dyslexic subjects were compared to that of controls by performing a point-to-point *t*-test between every data point of the responses (Matlab). Therefore, instead of component amplitudes and peak latencies significantly different ($P<0.05$ and $P<0.001$) latency ranges are reported in Section 3.

3. Results

3.1. ERPs to words, number-words and pseudowords in good readers

ERPs to words, number-words and pseudowords revealed condition-related differences in good readers. Fig. 1 shows ERP changes elicited in the three conditions. As can be seen on the superimposed curves, all three stimulus types elicited responses with similar wave structure. The typical wave structure recorded over the Cz site (left panel, middle window of the second row) can be characterized by a negativity of 100 ms, the vertex N100 followed by a positive wave of approximately 200 ms, called P150. The P200 is followed by a negative-going wave hardly reaching the baseline, which is labeled here as N350 (or RP). The last component of the fronto–central leads is a late positive component (LPC) with a maximal amplitude between 400 and 600 ms. At occipital sites a different structure can be seen, the first positive component, seemingly the counterpart of the vertex N100 is followed by a negative component, labeled as N150. The negativity at approximately 350 ms, clearly visible on the fronto–central leads, is less evident on the parieto–occipital responses. The first three waves of the parieto–temporal responses are followed by the LPC, though with larger amplitude than on the fronto–central electrodes.

The amplitude distribution of the first two peaks of the responses did not show differences among the three conditions, therefore, the top and back views of the distribution maps are shown here only for the word condition. As it can bee seen on Panel B of Fig. 1, the N100/P100 distribution is quite symmetric with a slight left preponderance over the left occipital lead. A distribution asymmetry of the N150/P150 components can be seen on the maps. It can also be seen that the P150 occurs with increased amplitude over the right frontocentral areas, while the N150 is most evident on the left occipital leads. Distribution maps computed for the peak amplitude of LPC are shown in Panel C. The LPC distribution in the word and pseudowords condition shows a similarity that can be characterized by symmetry and centroparietal maximum. The LPC amplitude is larger in the number-word condition as can be seen on the distribution map as well as on the corresponding ERP shown for the Pz electrode. Moreover, the maximum is somewhat more posterior than in the other two conditions.

The full ANOVA is shown in Table 1; here we report *P*-values, epsilon-corrected by the more conservative Greenhouse–Geisser method. N100, measured as the maximal negative peak occurring in the 80–140 ms (LW1), showed main effects of recording site ($F(11,121)=3.02$, $\varepsilon=0.198$, $P<0.025$) and a significant condition/recording site interaction ($F(22,242)=2.65$, $\varepsilon=0.198$, $P<0.021$). According to the post hoc analysis, N100 amplitude was larger for words and pseudowords than for number-words over most of the analyzed electrodes. Significant differences were found in W–NW and NW–PSW comparisons over the Pz, P4 and Oz sites. The maximal positivity (corresponding to P100) in LW1 showed a significant electrode main effect ($F(11,121)=10.17$, $\varepsilon=0.161$, $P<0.001$). For latency no significant effect was found in this window. In LW2 the positive and negative maxima (corresponding to P150 and N150) showed an electrode main effect only. In the latency window of 200–400 ms (LW3), no significant effects were found.

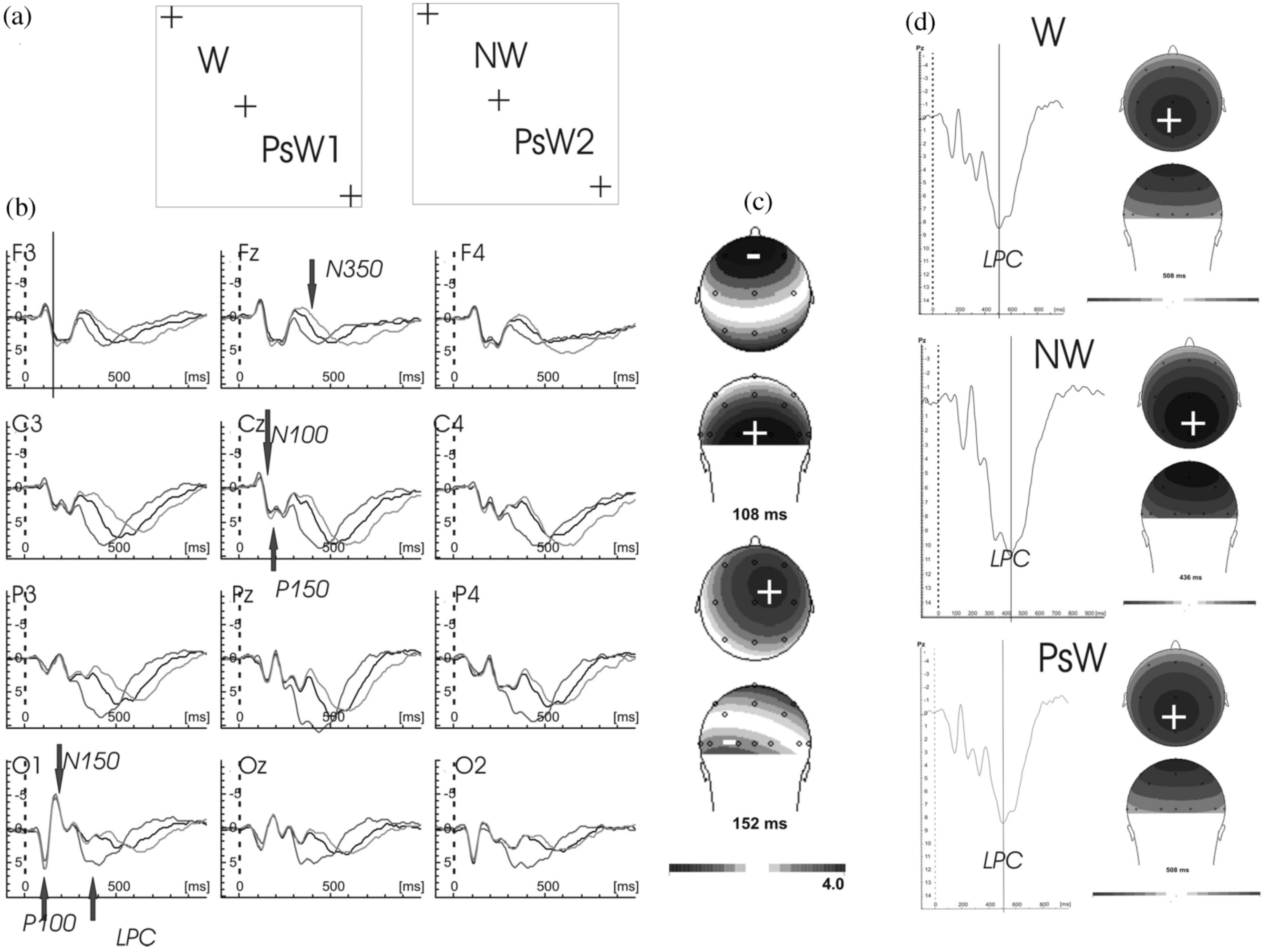

Fig. 1. ERPs elicited by words, number-words and pseudowords in good readers. Responses to the three stimulus types are shown at 12 electrode sites included in the statistical analysis. Panel (a): schematic drawing of the experimental design. Panel (b): ERP waveforms with labels for the most characteristic components. Panel (c): Amplitude distribution maps computed at the peak latency of the P100/N100 and N150/P150 waves. (d): Amplitude distribution of the LPC of ERPs elicited by three stimulus types. W: words, NW: number-words, PsW: pseudowords. Negativity is upward. For further details see text.

Table 1
Summary of the ERP differences between stimulus types in good readers. GG: Greenhouse–Geisser correction, H-F: Hujnh–Feldt correction for epsilon

LW1_min_Ampl	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	3,017626	0,069487	0,978958	1,957916	21,53707	0,070871	1,000000	2,00000	22,0000	0,069487
ELECTRODE	11	3,668927	0,000164	0,198988	2,188872	24,07759	**0,037217**	0,250370	2,75407	30,2948	**0,025704**
WORDNESS*ELECTR.	22	2,652415	0,000145	0,278943	6,136745	67,50420	**0,021888**	0,669594	14,73107	162,0418	**0,001372**

LW1_max_ampl	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	0,00008	0,999924	0,813069	1,626137	17,88751	0,999598	0,934175	1,868349	20,55184	0,999863
ELECTRODE	11	10,17466	0,000000	0,161307	1,774375	19,51812	**0,001285**	0,190108	2,091186	23,00304	**0,000597**
WORDNESS*ELECTR.	22	1,64560	0,037777	0,165872	3,649182	40,14101	0,185974	0,258414	5,685108	62,53618	0,153103

LW2_max_ampl	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	0,585959	0,565025	0,720186	1,440372	15,84409	0,514786	0,799428	1,598855	17,58741	0,530658
ELECTRODE	11	8,061108	0,000000	0,147494	1,622437	17,84681	**0,004847**	0,169352	1,862877	20,49164	**0,003066**
WORDNESS*ELECTR.	22	1,381517	0,123584	0,139103	3,060271	33,66298	0,265055	0,198789	4,373355	48,10690	0,252013

LW2_max_ampl	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	0,219122	0,804956	0,808354	1,616709	17,78379	0,759087	0,927207	1,854414	20,39855	0,788981
ELECTRODE	11	4,517196	0,000010	0,176726	1,943985	21,38384	**0,023910**	0,214100	2,355100	25,90610	**0,016456**
WORDNESS*ELECTR.	22	1,909064	0,009986	0,179733	3,954133	43,49546	0,126716	0,293206	6,450533	70,95586	0,086230

LW3	no significant effect at all

LW4_Ampl	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	1,34355	0,281500	0,791353	1,582706	17,40976	0,280412	0,902195	1,804389	19,84828	0,281344
ELECTRODE	11	13,59914	0,000000	0,293724	3,230963	35,54059	**0,000003**	0,430281	4,733090	52,06399	**0,000000**
WORDNESS*ELECTR.	22	2,46596	0,000440	0,185052	4,071141	44,78256	0,057495	0,307369	6,762109	74,38320	**0,026227**

LW4_Lat	Df	F	p	G-G Epsilon	G-G Adj. df1	G-G Adj. df2	G-G Adj. p	H-F Epsilon	H-F Adj. df1	H-F Adj. df2	H-F Adj. p
WORDNESS	2	17,46049	0,000029	0,774080	1,548160	17,02976	**0,000172**	0,876968	1,753936	19,29329	**0,000076**
ELECTRODE	11	1,07059	0,390580	0,263444	2,897885	31,87674	0,373831	0,367745	4,045194	44,49713	0,382736
WORDNESS*ELECTR.	22	2,19056	0,002146	0,200833	4,418317	48,60148	0,077886	0,352354	7,751786	85,26964	**0,037531**

As seen on the original curves and distribution maps shown in Fig. 1, the largest difference between the ERPs elicited by words, number-words and pseudowords was present in the latency range of the LPC (400–800 ms). There was approximately 100 ms latency difference among the peaks of the LPC to the three different stimulus types. These differences are reflected in a significant condition main effect for latency ($F(2,22)=17.46$, $\varepsilon=0.774$, $P<0.0001$) and an electrode main effect for amplitude ($F(11,121)=13.60$, $\varepsilon=0.293$, $P<0.00003$). Electrode by condition interactions were significant only when the more liberal Huynh–Feldt epsilon correction was used. The peak latency of LPC was shorter to number-words than to words in all centroparietal and occipital recordings except Cz. The LPC latency was the longest in all recordings but two (Fz and F4) to pseudowords.

3.2. ERPs in dyslexics

3.2.1. Waveform changes of the ERPs

Fig. 2 shows averaged ERPs recorded in dyslexics. The ERP waveforms show characteristic differences as compared to the controls. Horizontal lines over the responses show results of the point-to-point *t*-tests used for comparing dyslexics and controls. As this figure shows, the occipital P100 elicited by words, number-words and pseudowords increases while the vertex N100 decreases to pseudowords and increases to number-words. The amplitude of the N100 to words and pseudowords did not differ between dyslexics and controls. However, the N100 to number-words was nearly twice as large in dyslexics as in controls, as shown by the horizontal line representing results of the point-to-point *t*-test. In dyslexics, contrary to the control group, the N350 wave was different for all three-stimulus types. Words and number-words elicited even larger LPCs than in controls. This difference diminished when pseudowords were read.

3.2.2. The early components: P100/N100 and P150/N150

Fig. 3 demonstrates the early component correlates of reading words and pseudowords. The large increase of the P100 amplitude is well demonstrated by the distribution map computed for the peak, whose latency was also 40 ms longer in dyslexics than in controls. In contrast to this, the vertex N100 did not change. However, striking differences were found between controls and dyslexics when amplitude distributions of the N150/P150 peaks were compared. As can be seen on Fig. 3, the amplitude distribution of these components occurred 40 ms later in dyslexics. Controls showed a right lateralized distribution of the P150 and a left lateralized maximum of the N150. The opposite can be seen on the distribution maps of dyslexics.

4. Discussion

4.1. Processing differences found in control subjects

The main results of our study demonstrated that changes of the ERPs to visually presented words, number-words and pseudowords recorded during a lexical decision task correlate with different steps of the lexical and early semantic access. As revealed by our data the first sensory stage of lexical access differs according to the lexical status of the stimuli used as well as to the type of words presented. An unexpected result of the study was that the responses elicited by number-words differed from other content words even in this first stage of lexical access, as shown by the significant increase of the vertex N100 and occipital P100. However, the P150 wave following the vertex N100 as well as its occipital counterpart the N150, assumed to be associated with lexical selection, did not reveal processing differences between words and pseudowords. It seems that in this stage of the processing no further step is needed. The third component analyzed, the N350, co-occurring with a hardly identifiable small parieto–occipital wave in the same latency range, showed a slight left preponderance. This component, assumed to be the RP, was larger to words than to number-words, though a significant difference was not found in the analyses. Moreover, no difference was found between words and pseudowords, which suggest that the RP is not sensitive to wordness in a transparent orthography. However, if we believe

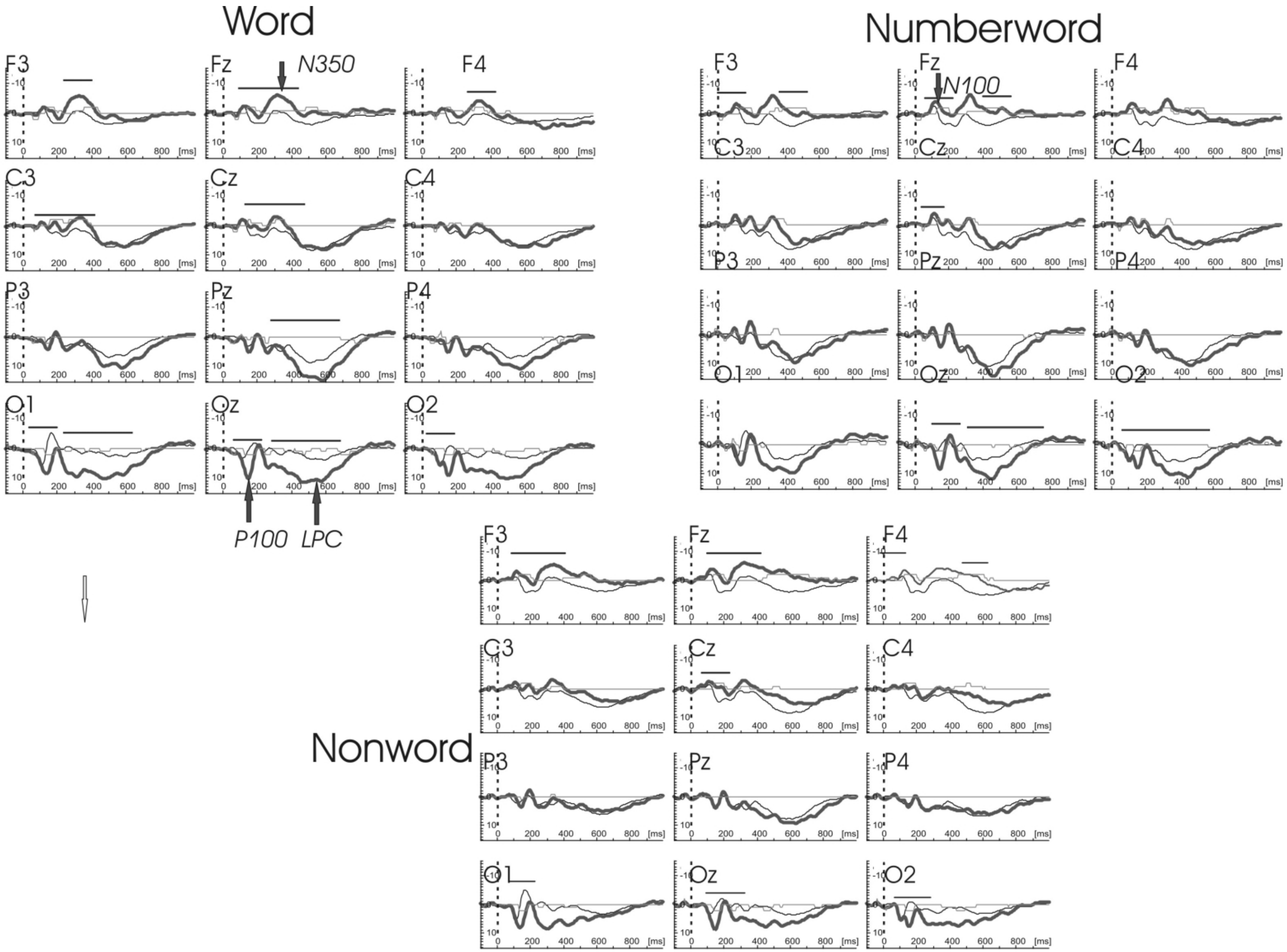

Fig. 2. ERPs elicited by words, number-words and pseudowords in adult well compensating dyslexic subjects as compared to controls. Thin line: controls, Thick line: dyslexics. Horizontal lines represent the significant differences (Point-to-point *t*-test, see text).

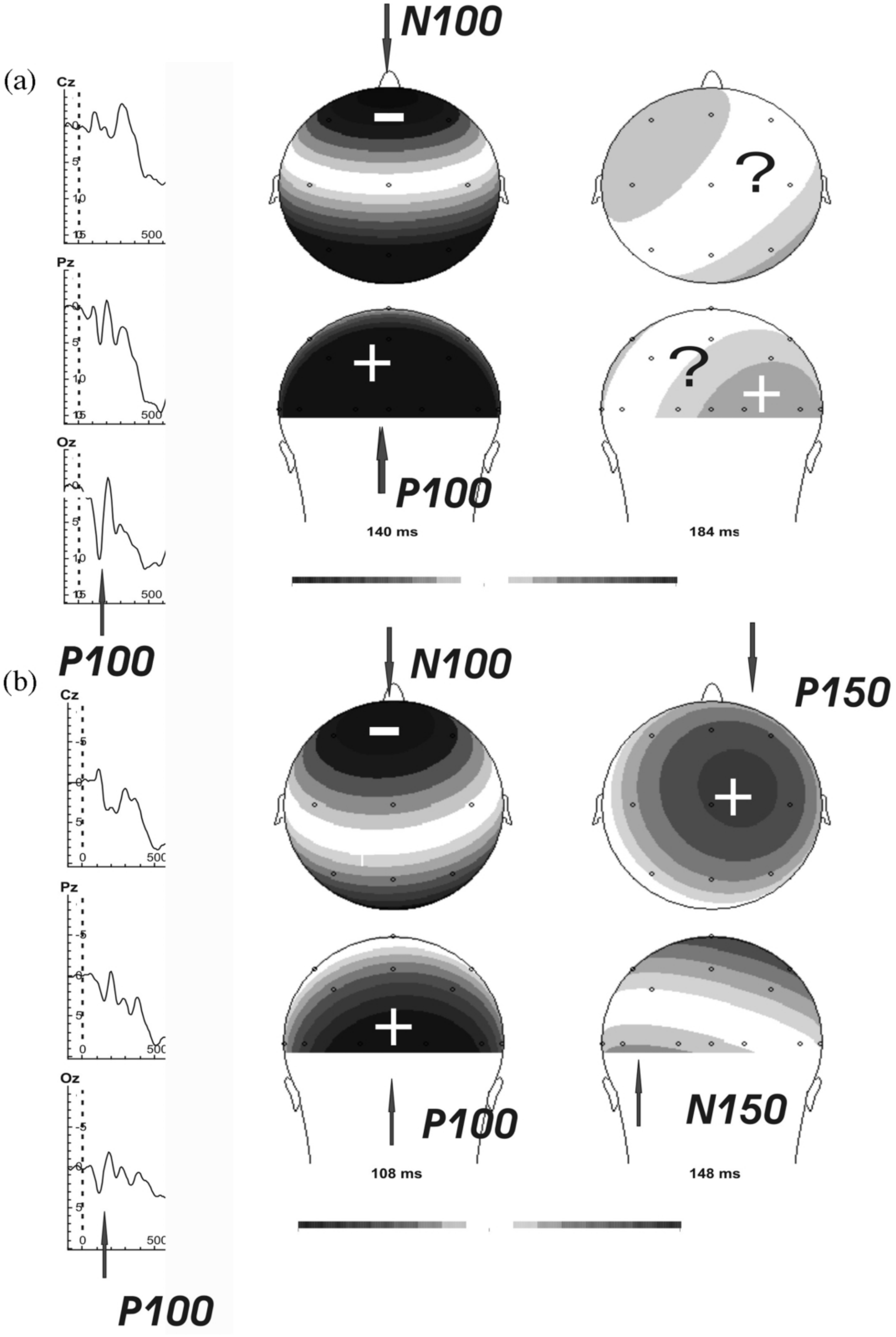

Fig. 3. ERPs over three recording sites and amplitude distribution maps in the word condition: (a): dyslexics, (b): controls. Amplitude maps are computed at the peak latency of P100/N100 and N150/P150 waves. Note the latency difference between the peak latencies.

that the N350 corresponds to the well-documented recognition potential, an explanation is needed as to why its changes are not consistent with the 'wordness' of the stimuli presented. We may assume that in our paradigm the RP more strongly correlates with the representational goodness of the words, than with the lexical status of the letter strings. This finding would only partially support the suggestion of Martín-Loeches et al. (1999) stating the RP is associated with the lexical selection. However, our RP-like component definitely peaks later than the classical RP does and it is hard to believe that the second step of lexical access occurs so late in normal readers.

A significant and not expected result of the study was the wordness sensitivity of the late positive component, LPC. The LPC to number-words showed a significant difference in all parieto–occipital recordings as compared to words or pseudowords and this was the case both for latency and amplitude. This suggests that the third phase of processing, that is the early semantic access, relies on different retrieval processes. The occurrence of a significantly earlier and larger LPC may be explained in two ways, as words and number-words may differ in two aspects. First, the written form of digits may have weaker representation in the sight-word vocabulary and reading requires more effort. Second, the early semantic access may need an additional access to the abstract representation of numbers. This assumption that differences in retrieval lead to distinct processing strategies may explain the striking differences found. The consistent finding in all subjects, that is the amplitude increase of the early components to a special class of content words, e.g. number-words, suggests that increased activity is required as early as the sensory stage of lexical access and the processing differences are present in a later stage that is the early semantic access. The differences found suggest that reading number-words is a challenging task even for good readers and the additional effort is reflected by an increase of the early ERP components as well as by the late ones. It seems that conclusions drawn from the results of pseudoword reading as compared to reading number-words are not necessarily valid in general. The enhancement of the N100 and P100 to number-words may magnify the differences found in comparison to pseudowords, especially when processing differences between good and poor readers are studied. Therefore, we suggest that the differences found between number-words and pseudowords in the Wimmer et al. (2002) study needs further proof before we draw conclusion on reading differences between pseudowords and words in general.

4.2. ERP correlates of compensation strategies used in reading by dyslexic adults

Our results clearly demonstrate that the reading strategy used by the young adults participating in our study, compensates successfully for their reading problems of developmental origin and their strategy may rely on different cortical processes. First, additional processes are allocated to the stimuli even at the sensory phase of lexical access as shown by the occipital P100. This effect may be partly due to additional attention allocated to the reading performance as reflected by an enhanced vertex N100. The attenuation of the N100 to pseudowords is absent in our dyslexic subjects and this would mean that the mini-neglect hypothesis of Hari and Renvall (2001) shown in 12-year-old boys in a number-word vs. pseudowords task by Wimmer et al. (2002) cannot be demonstrated in adults. However, it is also possible, that the attention deployment can be demonstrated in children while in adults it is not visible probably due to these processes playing a particular role in reading compensation. The compensation may rely on processes participating in lexical selection. This assumption is based on the large increase of the N350 in dyslexics as compared to controls. Visual inspection of the ERPs as well as results of the point-to-point *t*-test show that this selection is less evident for number-words than for words. From this point of view reading words is different from reading number-words, while reading words do not differ greatly from pseudowords. This would mean again that the processing differences between words and pseudowords, proposed by Wimmer et al. (2002), that is a different strategy used by dyslexics, might not be valid for words in general. However, as shown by our ERP results processes allocated to lexical decision during reading may be quite different in dyslexics compared to good readers and this difference may be related either to the lexical or to the early semantic access. It appears that both stages of the lexical access are effortful as revealed by the increased P100 and N3500 waves. Also, the early semantic access may help compensation processes in a particular way as shown by changes of the late positive component. Additional processes may be allocated to words having a better representation in sight word vocabulary. The LPC to words in dyslexics was five times larger than in controls, while their LPC to number-words was almost the same size as that of the controls, except occipitally. Moreover, the dyslexics' LPC to pseudowords did not show any particular differences compared to controls, suggesting an early closure of the processing. We assume that this difference demonstrates in adults the suggestion of Wimmer et al. (2002), of a different strategy used by poor readers; that is an early closure of the lexical processing of pseudowords.

As we mentioned in Section 1, many researchers have proposed that subsystems of the posterior cortical reading system play a distinct role in linguistic analysis of printed words (Frackowiak et al., 1997; Pugh et al., 2000, 2001; Tagamets et al., 2000). Our ERP data on young adults without reading difficulty are partly in agreement with the notion that the ventral circuit of the posterior reading system is sensitive to both word frequency and lexical status. It seems that the fast orthographic processing of words and pseudowords does not really differ in a transparent language like Hungarian, at least not in adults. However, distinctions between words of different representation in the sight word vocabulary may modify the early ERP components, most probably generated by areas of the ventral circuit. We have also demonstrated that reading letter strings of low sight word frequency may rely on a concerted action both of fast, early and most probably ventral and of late, slow, attentive processes assumed to originate in the dorsal circuit.

Our data on the adult dyslexics is in agreement with the findings of Shaywitz et al. (2002) in children, showing that during word and pseudowords reading tasks anomalous activation occurs both in the ventral and dorsal sites. Our results show that despite a significant processing time delay shown by the early components, compensation is possible as the strategy used relies on both systems. It is possible that dyslexics cancel any furthermore processing of pseudowords after lexical selection and an indirect processing takes place in a later stage for words. It is highly probable that the wordness effect found for the LPC reflects one very important aspect of the reading performance, that is the processing effort associated with parieto–occipital activity. This processing effort is shown by controls only when letters of low sight word frequency are shown. From a developmental point of view it is very important to clarify whether dyslexic children may develop a similar strategy found in adults. We may assume that compensation relies heavily on the extent of anomalous activity of the different subsystems of the posterior reading system. Successful compensation may rely on homologous right posterior areas (Paulesu et al., 2001; Simos et al., 2000, 2002), although the present ERP data do not provide sufficient evidence.

In spite of the fact that dyslexia is traditionally defined as a discrepancy between reading ability and intelligence and adequate teaching method used in reading acquisition, it is left open how many different forms it may take. Although it is well established that dyslexia is associated with brain activity anomalies, the behavioral variations are only partially linked to the brain processes assumed. A multiple case study of Ramus (2003) assessed three leading theories of developmental dyslexia. Their behavioral data showed low level auditory and visual deficits as well as language-related deficits, which might contribute to dyslexia to differing extents. We may speculate that the ERP profiles found give us further information about the possible strategies subjects use. It seems that a higher level, more complex, therefore, higher cost processing, as revealed by the delayed and low amplitude P100 component, may compensate low level deficits. Furthermore, dyslexics who do not compensate well may differ for various reasons. First, those whose auditory deficits lead to an underdefined language representation may not rely on higher-level compensation. However, those whose deficit in phonology is not linked to early processing problems may overcome this problem by extending processing to other cognitive processes and this would be shown by ERP differences. The aim of our ongoing study on dyslexic children is to develop experimental paradigms to judge the validity of these assumptions.

In summary, our results suggest that in good readers additional activity occurs in the sensory or selection stage of the lexical access when words of low sight frequency, e.g. number-words are read. Significant processing differences between words and number-words may occur in a later stage of the processing that is the early semantic access, therefore, we do not suggest number-words be used for judging general differences in lexical processing. Our results also show that young adults may develop a particular compensation strategy for reading words of different frequency. However, processing differences between words and number-words may also be explained in other ways. For example, as number-words represent a smaller set of words than frequent nouns, they may be more difficult to recognize; this is quite possible, as good readers showed similar ERP correlates, as did dyslexics. However, if the change found was related only to set size, the LPC to words recorded in dyslexics would not have differed from that of controls. Our data show that: (1) The lexical access is fast and accurate in good readers, although the early components do not differ between words and pseudowords. This effect may rely on the transparency of the Hungarian orthography. (2) Attentional effort is shown by the early ERP components to number-words. (3) Number-words require furthermore processing for early semantic access. (4) Weakly defined sight word vocabulary of dyslexics may be compensated during lexical selection as well as in a later stage that is the early semantic access. (5) Dyslexic adults compensating well for reading difficulties, differ markedly from good readers in this later stage, when words are read. (6) The LPC reflects additional activation allocated to word reading when low frequency words like number-words are read. This effect is shown by good readers as well, therefore, the largest difference found between dyslexics and controls is found for frequent words. (7) The early semantic access is absent in dyslexics; perhaps one of the strategies used by dyslexics in a transparent orthography.

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