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The electrophysiological correlates of developmental dyslexia: New insights from lexical decision and reading aloud in adults

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Abstract

Many studies have described the electrophysiological specificities of print processing in dyslexic readers, mostly using lexical decision tasks. The aim of the present study was twofold : a) to assess for the first time the electrophysiological correlates of print processing in dyslexic adults in the under-investigated context of reading aloud tasks, acknowledged to be especially relevant to investigate phonological processes relatively to lexical decision; and b) to assess whether the electrophysiological specificities described in dyslexic readers in lexical decision correspond to a different neuronal network engaged in print processing. 21 dyslexic university students and matched controls performed a lexical decision task and a reading aloud task on words and pseudowords under EEG recording. In lexical decision, the pattern of results indicates the engagement of similar brain processes between the groups, but with a sub-efficient visual word form processing in dyslexia. In reading aloud, between group differences revealed completely different distributions of the electric field at scalp between the two groups after the N2 time window, suggesting alternative processing strategies in dyslexic readers. Those specificities seem to be related to their core phonological deficits. Crucially, the present results suggest that the nature of electrophysiological divergences in print processing in dyslexic readers vary according to the task: while lexical decision task appears to be well suited to assess divergences in lexical access, reading aloud tasks should also be used in ERP investigation as it allows a better insight into phonological processes and thus be better suited in the framework of the phonological deficit theory of dyslexia.

Keywords: Developmental dyslexia, ERP, Phonological deficit theory, Lexical access, Reading aloud, Lexical Decision.

1. Introduction

One of the major goals of primary education concerns the acquisition of print to sound mapping rules in order to enable the efficient decoding of printed words. The development of expert reading skills requires not less than five years of academic training in a specific writing system (Aghababian & Nazir, 2000). However, despite adequate instruction, 3 to 7 % of the population fail to acquire expert reading skills (Lindgren, De Renzi, & Richman, 1985). Developmental dyslexia is defined as impaired reading acquisition that occurs despite normal intelligence, adequate schooling and in the absence of other cognitive, sensory, psychiatric, or motivational disorders (World Health Organization, 2008). Considering the impact of this learning disorder on education as well as social and professional integration, understanding the factors contributing to developmental dyslexia has become one of the major goal of scientific research. Electrophysiological studies have allowed to assess the differences in the time course of print processing between dyslexic and expert readers in relation to the major explicative theories of developmental dyslexia. The present experiment aims at further understanding the neurophysiological specificities in print processing in dyslexic readers based on a new approach. First, we investigated the electrophysiological specificities of print processing in dyslexic university students beyond the known and over-investigated context of lexical decision, i.e., also in the under-investigated context of reading aloud, which is closer to reading in real life and may be better suited to capture their core phonological impairments. Second, we performed waveform amplitude and spatio-temporal analyses on the event-related electrophysiological data collected in the lexical decision and the reading aloud tasks. This combined analysis allowed us to go deeper in the interpretation of the electrophysiological specificities of dyslexic readers and to assess whether different underlying processes (different distributions of the global electric field at scalp) are engaged in dyslexic readers relative to unimpaired controls.

The next subsections summarize the major hypotheses and electrophysiological findings in developmental dyslexia and the interest of the reading aloud task relatively to the investigation of the major phonological deficits of dyslexic readers.

1.1. Developmental dyslexia: impaired visual word recognition

In typical readers, with reading practice, a fast and parallel processing of familiar words emerges, as supported by the disappearance of the word length effect several years after the beginning of reading instruction (Zoccolotti, de Luca, di Pace, Gasperini, Judica, & Spinelli, 2005). In contrast, in dyslexic readers, this word length effect persists, suggesting a lack of automatization of familiar words processing in this population. This lack of fast and parallel processing of print has been supported by EEG data investigating the patterns of the N170 component specialization in this population using visual or orthographic decision tasks. Event related potential (ERP) studies have associated the left N170 component (or N1/N2), which peaks at around 200 ms at occipito-temporal sites, with the expert processing of print. Experimental data have shown larger left N170 amplitude for wordlike stimuli compared to visual non-orthographic stimuli such as symbol strings in adult expert readers (Brem, Bucher, Halder, Summers, Dietrich, Martin et al., 2006; Maurer, Brem, Bucher, & Brandeis, 2005). This tuning for print has been reported to be lacking in both dyslexic children using immediate repetition detection (Maurer, Brem, Bucher, Kranz, Benz, Steinhausen, et al., 2007) or letter/symbol decision task (Araújo, Bramão, Faísca, Magnus Petersson & Reis, 2012) and dyslexic adults using lexical decision tasks (Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Mahé, Bonnefond, & Doignon-Camus, 2013). Lexical decision experiments have also revealed an impaired fast lexical access in dyslexic adults, with a lack (Mahé et al., 2013; Shaul, Arzouan, & Goldstein, 2012) or reverse (Dujardin, Etienne, Contentin, Bernard, Largy, Mellier, et al., 2012) lexicality effect on the N170 (i.e., amplitude difference between words and pseudowords) compared to expert readers. Taken together, these data suggest that in the context of visual word recognition, dyslexic readers present impairments in the early differentiation between verbal and nonverbal visual stimuli, and between familiar and unfamiliar orthographic forms. This pattern of data is in line with brain imaging studies describing in dyslexic readers an impaired specialization for print of specific brain areas with reading acquisition (Paulesu, Demonet, Fazio, McCrory, Chanoine, Brunswick, et al., 2001). However, it should be noted that the ERP studies described above were limited to waveform amplitude analyses, which can hardly inform on whether different underlying brain processes are involved. The use of spatio-temporal analyses would allow to go deeper in the interpretation of the deficits in developmental dyslexia. Indeed, topographic analyses allow to divide the ERP signal into periods of stable or quasi-stable global electric fields at scalp (or microstates), likely to correspond to particular periods in mental information processing (Changeux & Michel, 2004; Koukou & Lehman, 1987; Lehman, Strik, Henggeler, Koenig, & Koukou, 1988). Spatio-temporal segmentations would thus allow to determine whether the differences observed between expert and dyslexic readers are related to the recruitment of different neural networks between the two groups. This would be indicative of alternative processing strategies in dyslexic compared to expert readers.

1.2. Developmental dyslexia: the phonological deficit theory

The phonological mapping theory has linked the impaired specialization for print observed in developmental dyslexia to their core phonological deficits (Maurer & McCandliss, 2007; McCandliss & Noble, 2003). This theory postulates that decoding ability affects the gradual specialization of neural networks for print processing during the early years of reading. In this way, the impaired brain specialization for print described in dyslexic readers would be a consequence of their core phonological deficits. More precisely, the currently most established causal hypothesis of dyslexia identifies a deficit in the access to phonological representations from print (Blomert, 2010; Ramus & Szenkovits, 2008). In support, differences between expert and dyslexic readers have been reported on specific ERP components related to phonological analysis such as the N320 component. This component has been related to grapheme-to-phoneme conversion, supported by its larger amplitudes at left central sites in response to phonologically legal (e.g., words, pseudowords) compared to phonologically illegal stimuli (e.g., pseudoletters strings) in rhyme judgment (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999), silent reading (Simon, Bernard, Largy, Lalonde, & Rebaï, 2004) or lexical decision tasks (Simon, Bernard, Lalonde, & Rebaï, 2006). In developmental dyslexia, an impairment in the N320 response classically observed in expert readers (i.e., larger N320 left amplitudes for phonologically legal vs. illegal stimuli) has been reported in both dyslexic children (Araújo et al., 2012) and adults (Araújo, Faísca, Bramão, Reis, & Peterson, 2015) in letter/symbol decision tasks. This pattern of data has been taken as an evidence of impairments in later stages of phonological analysis. In support, impaired responses have also been observed in dyslexic readers at other late ERP components which have been related to phonological processing (Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013; Savill & Thierry, 2012). Taken together, all these ERP findings provide further support for the phonological deficit theory of developmental dyslexia.

1.3. Developmental dyslexia research: the interest of the reading aloud task

Altogether, ERP experiments investigating the time course of print processing in developmental dyslexia support an impaired specialization for print in relation to phonological deficits in this population. It should be noted that such results derive from decisional tasks focused on different linguistic aspects: perceptual for letter decision, orthographic for lexical decision, phonological for phonological decision, or semantic for semantic decision. To our knowledge, no data is currently available concerning the neurophysiological differences in print processing between dyslexic and expert readers in the context of a reading task (either silent or aloud). This appears surprising, especially in a population likely characterized by core phonological deficits and considering the behavioral studies highlighting the strongest sensitivity to phonological decoding of the reading aloud tasks relative to the lexical decision tasks (Ferrand, Brysbaert, Keuleers, New, Bonin, Méot, et al., 2011; Katz, Brancazio, Irwin, Katz, Magnuson, & Whalen, 2012). A recent meta-analysis has considered behavioral studies performed with dyslexic children based on lexical decision and reading aloud (Zoccoloti, De Luca, Di Filippo, Marinelli, & Spinelli, 2017). The authors support the idea that the reading task is a determinant tool for the understanding of print processing in developmental dyslexia. This is fully in line with the concept of functional overlap introduced by Grainger & Jacobs (1996), which stipulates that the combination of different experimental contexts (e.g., lexical decision, reading aloud, perceptual identification) is crucial to understand the cognitive processes involved during print processing and to improve the cognitive models of print processing. Each experimental task would indeed be biased in favor of specific processing stages (Balota & Yap, 2006). The lexical decision task puts a heavy weight on orthographic analysis while it does not explicitly require associating the result of the orthographic analysis to a specific phonological output. Additionally, this task implies an explicit choice between two alternatives. The reading aloud task also involves an orthographic analysis but the focus is on the establishment of a precise correspondence between the orthographic and the phonological forms of the word. An implicit choice among thousands of alternatives is requested to perform the task. In order to determine whether these task specificities are related to differences in the processing stages of print processing, Mahé, Zesiger and Laganaro (2015) have compared the time course of print processing between lexical decision and reading aloud in adult expert readers. Results revealed a completely distinct time course of print processing between the two tasks from about 140 ms after stimulus presentation, i.e., as early as the N170 component, with a predominance of orthographic word form analysis in the lexical decision task only. As the two tasks imply different processes, one might hypothesize that different patterns of print processing impairments would emerge in dyslexic readers in the two tasks. Furthermore, given the tasks properties, an approach combining both lexical decision and reading aloud appears to be especially relevant to assess both impairment in visual word form analysis and in phonological processes in dyslexia.

1.4. Aim of the present study

The present study aims to describe the electrophysiological signature of impaired print processing in developmental dyslexia in the context of both lexical decision, a task especially relevant to assess orthographic processes, and reading aloud, better suited to assess phonological processes. The main goal is to determine whether dyslexic university students display similar patterns of diverging print processing relatively to expert readers in each context of print processing or whether each context allows to highlight some specificities. In addition, we combined waveform amplitude analyses with spatio-temporal analyses, which allowed us to determine whether between group differences in print processing correspond to different underlying neurophysiological mechanisms.

2. Method

2.1. Participants

The study was conducted at Geneva and Lille universities, with exactly the same experimental procedures and the same recording material. Twenty-one university students with a diagnosis of developmental dyslexia (6 men, mean age 22.6 years, ± 4.4 years, 7 from Geneva) and 21 age matched controls (4 men, mean age 21.2, ± 2.3 years, 8 from Geneva) took part in the experiment. All were native French speakers and right-handed as determined by the Edinburgh Handedness Scales (Oldfield, 1971; mean lateralization quotient index range: 85%; range: 60–100%) with normal or corrected-to-normal vision. All dyslexic participants have been diagnosed by a speech and language therapist (mean age of diagnosis: 7.4 years; range 5 to 14 years) and have completed several years of remediation training (mean 6 years; range 0.5 to 13 years), with no current remediation. Apart four dyslexic participants who had also a diagnosis of dysorthographia, they reported no other neurodevelopmental disorders (e.g., dysphasia, or attention deficit-hyperactivity disorder). All participants gave their written informed consent and the study protocol was approved by the local ethics committee.

Assessment of reading and other cognitive functions

Prior to the ERP experiment, all participants took part to a behavioral session evaluating reading skills, reading related skills (i.e., phonological and visuo-attentional skills) and nonverbal intelligence.

Reading skills were assessed with one minute text reading and word list reading (comprising regular words, irregular words and pseudowords) from the ECLA 16+ battery (Gola-Asmussen, Lequette, Pouget, Rouyer, & Zorman, 2011).

Phonological skills were evaluated through phonological awareness tasks (i.e., phoneme deletion and spoonerisms from the ECLA 16+; Gola-Asmusen et al., 2011) and rapid picture and letter naming (RAN) taken respectively from the Evalad battery (George & Pech-Georgel, 2011) and the ECLA 16+ battery (Gola-Asmussen et al., 2011). Visuo-spatial attention skills were evaluated with global and partial visual span tasks from the Evadys battery (Valdois, Guinet, & Embs, 2014).

Nonverbal intelligence was assessed by the short version of Raven’s Progressive Matrices (Raven, Raven, & Court, 1998) performed under unlimited time conditions.

As displayed in Table 1, expert readers and dyslexic readers were well matched on length of college studies and nonverbal intelligence. In contrast, expert readers scored better than dyslexic readers on almost all measures of reading and reading related skills.

Table 1. Group characteristics (significant group differences are marked in bold letters)

	Dyslexic readers	Expert readers	Group difference (t-test)
Education (years of college studies)	2.8 (1.4)	2.3 (1)	t(40)=1.28, p>.10
Text reading (words correctly read)	**152.9 (±19.8)**	**177.4 (±13.6)**	**t(40)=-4.68, p<.001**
Text reading (number of errors)	1.6 (±1.2)	1 (±1.2)	t(40)=1.65, p>.10
Regular word reading (RTs in seconds)	**17.1 (±5.1)**	**12.3 (±2.7)**	**t(40)=3.77, p<.001**
Regular word reading (score/20)	**19.1 (±1.1)**	**19.7 (±.6)**	**t(40)=-2.12, p=.040**
Irregular word reading (RTs in seconds)	**15.9 (±4.7)**	**11.9 (±2.8)**	**t(40)=3.35, p<.01**
Irregular word reading (score/20)	18.2 (±1.7)	18.3 (±1.6)	t(40)=-.09, p>.10
Pseudoword reading (RTs in seconds)	**29.7 (±12.3)**	**17.7 (±3.9)**	**t(40)=4.27, p<.001**
Pseudoword reading (score/20)	17 (±.2.3)	18.3 (±2)	t(40)=-1.87, p=.068
Phoneme deletion (RTs in seconds)	**41.4 (±12.4)**	**31.2 (±13.7)**	**t(40)=2.53, p=.016**
Phoneme deletion (score/10)	7.8 (±2.4)	9.1 (±2)	t(40)=-1.97, p=.055
Spoonerisms (RTs in seconds)	**139.3 (±59.1)**	**80.3 (±37.6)**	**t(40)=3.86, p<.001**
Spoonerisms (score/20)	**17.1 (±2.6)**	**19.2 (±1.1)**	**t(40)=-3.38, p<.01**
RAN picture (RTs in seconds)	**45.8 (±6.9)**	**38 (±4.8)**	**t(40)=4.22, p<.001**
RAN picture (score/60)	60 (±0)	59.9 (±.5)	t(40)=1.37, p>.10
RAN letter (RTs in seconds)	**24.3 (±6.6)**	**16.5 (±3.5)**	**t(40)=4.73, p<.001**
RAN letter (score/50)	49.3 (±1.2)	49.7 (±.6)	t(40)=-1.32, p>.10
Partial visual span (score/72)	**56 (±8.8)**	**62.1 (±7)**	**t(40)=-2.40, p=.021**
Global visual span (score/144)	**83 (±15.5)**	**106.2 (±20.4)**	**t(40)=-4.06, p<.001**
Non verbal intelligence (centile row)	80.7 (±14.3)	86.7 (±9.5)	t(40)=-1.58, p>.10

2.2. Material

To avoid item repetition across the reading and lexical decision tasks, two matched lists of stimuli were created and counterbalanced between the two tasks. Each list comprised a total of 120 mono and bisyllabic words selected from the French lexical database Lexique 3 (New, Pallier, Ferrand, & Matos, 2001). All words were four-to-eight letter long. Orthographically legal and pronounceable pseudowords were created by changing at least two letters in the set of words. The 240 words and 240 pseudowords were matched on bigram frequency, the number of orthographic and phonological neighbors and the frequency of the first syllable ($p>.10$). In addition, the two lists of words (Appendix A) and two lists of pseudowords (Appendix B) were matched on a set of pertinent variables.

2.3. Procedure

The participants were tested individually in a soundproof dimly lit room, sat at 60 cm in front of the computer screen. All participants performed both a lexical decision task and a reading aloud task in counterbalanced order, with an interval filled with an unrelated task in between. Each task was divided into 3 blocks of words and pseudowords presented in pseudorandom order (no more than 3 consecutive words or pseudowords).

The software E-prime (E-Studio) was used to present the trials and record the response latencies (RTs) and the errors for the lexical decision task. The procedure was the same in both lexical decision and reading aloud: each trial began with a black fixation cross presented for 400 ms in the centre of a grey screen (used to avoid extreme light exposure). The fixation cross was then replaced by a grey screen for 100 ms, followed by the stimulus for 1000 ms. Stimuli were presented in Courrier New font, with 18-point lower case letters and subtended approximately 3.6 degree of the visual angle. The next trial began after a random inter-trial interval of 1400-1600 ms. Before each experimental task, the participants performed six practice trials.

For both tasks, participants were instructed that they would see words and pseudowords on the computer screen. In the lexical decision task, participants were asked to decide as quickly and accurately as possible whether the stimulus corresponded to a real word or not by pressing a YES response key or a NO response key with the right hand. In the reading aloud task, participants were required to read aloud as quickly and accurately as possible the stimulus displayed, whether it was a word or a pseudoword. The spoken responses were digitized and recorded for later response latency and accuracy check. After elimination of errors, latencies of vocal responses (i.e., the number of ms separating the stimulus onset from the articulation onset) were systematically checked with speech analysis software (Check Vocal; Protopapas, 2007).

2.4. ERP recording and analysis

2.4.1. EEG acquisition and Pre-Analyses

EEG was recorded continuously using the Active-Two Biosemi EEG system (Biosemi V.O.F. Amsterdam, Netherlands) with 128 channels covering the entire scalp. Signals were sampled at 512 Hz and band-pass filters set between 0.16 and 100 Hz.

Offline, ERPs were then bandpass-filtered to 0.2–30 Hz and notch-filtered to 50 Hz and reaveraged to average references. Averaging was computed with epochs (i.e., specific time windows extracted from the continuous EEG signal) of 500 ms starting 100 ms before to 400 ms after stimulus onset using the Cartool software (Brunet, Murray, & Michel, 2011). Epochs contaminated by eye blinking, movements or other noise were rejected and excluded from averaging after visual inspection. In addition, only trials with correct responses and valid RTs were retained. As a result, a minimum of 55 averaged trials per participant in each condition and task entered the ERP analyses (dyslexics: 55-114 epochs [mean=93] in lexical decision; 64-112 epochs [mean=88] in reading aloud; controls: 61-116 epochs [mean=99] in lexical decision; 66-113 epochs [mean=98] in reading aloud). Bad channels (i.e., electrodes with artifacts or missing signal) were interpolated using 3-D splines interpolation (Perrin, Pernier, Bertrand, Giard, & Echallier, 1987). This procedure allows to reconstruct a missing or poor EEG signal from a specific electrode by combining signals from neighboring electrodes. On average 9 channels were interpolated for each participant. The number of averaged trials and interpolated electrodes did not differ between the two groups.

2.4.2. Waveform analyses

Standard amplitude waveform analyses were first performed on all electrodes and data-points (from -100 ms before stimulus presentation to 400 ms after) to identify separately for each task the time windows of between group differences. This analysis thus informs on whether and when differences in amplitudes appear between dyslexic and expert readers. Repeated measure ANOVAs (parametric analysis) were computed on ERP amplitudes separately for each task with the between factor group (i.e., dyslexic readers versus expert readers) and the within factor stimulus type (words versus pseudowords) using STEN toolbox (developed by Jean-François Knebel, http://www.unil.ch/fenl/home/menuguid/infrastructure/software--analysis-tools.html). To correct for multiple comparisons, a spatial and temporal correction criterion was applied: only differences over at least 4 clustered electrodes and extending over at least 5 consecutive time-frames (i.e., 10 ms) were retained with an alpha criterion of 0.02.

2.4.3. Global topographic ERP pattern analyses

Second, global topographic ERP pattern analyses were performed. The topographic analysis consisted in clustering the ERP signal (from 80 to 400 ms after stimulus onset) into different periods of stable or quasi-stable global electric fields, each assumed to correspond to particular periods in mental information processing (Changeux & Michel, 2004; Koukou & Lehmann, 1987; Lehman et al., 1998). The global topographic patterns further inform on the nature of the between group differences: a) whether they are limited to a mere difference in the strength of the electric field (i.e., only amplitude differences); b) whether different neurophysiological mechanisms underlie print processing between the two groups, with topographic differences; c) whether they rely on the involvement of similar neurophysiological mechanisms engaged for a shorter/longer time-period, in the case of similar microstates characterized by different durations or by shifts.

A spatio-temporal segmentation was run separately for each task. This spatio-temporal segmentation analysis (Brunet, et al. 2011) allows summarizing ERP data into a limited number of topographic map configurations. This analysis was applied in order to identify time periods during which dyslexic readers evoked different electric fields at scalp compared to expert readers for each task and stimulus type. The spatio-temporal segmentation was applied on the grand-averages for each kind of stimuli (i.e., words and pseudowords) from the dyslexic and the expert readers from 80 to 400 ms after stimulus presentation separately for each task. To determine the most dominant map configurations, we used a modified hierarchical clustering analysis (Pascual-Marqui, Michel, & Lehmann, 1995; Michel, Thut, Morand, Khateb, Pegna, & Grave de Peralta, 2001): the agglomerative hierarchical clustering (Murray, Brunet, & Michel, 2008). A modified cross-validation criterion was used to determine the optimal number of maps that explained the best the group-averaged data sets across conditions. Additionally, a given topography had to be present for at least 20 time-frames (i.e., 40 ms) to be further considered. Then, a procedure called “fitting” was applied to statistically test the presence in each individual data of the pattern of map templates observed in the grand-averaged data. During the fitting procedure, each of the map templates identified in the grand-averaged data is compared with the moment-by-moment scalp topography of individual subjects’ ERPs from each condition (each time point is labelled according to the map with which it best correlates spatially). This procedure allowed to establish the presence and the duration of each cluster map in each individual ERP, these measures being used then for the statistical comparisons between groups and conditions. .

In order to analyze whether some maps were more representative of one group compared to the other, the map presence and map duration in ms observed in each subject's data were used for statistical analysis. Repeated measure ANOVAs were computed for each task on map duration with the between subject factor Group and the within subject factor Lexicality. Concerning map presence, Pearson chi square were applied to compare dyslexic and expert readers on each condition.

3. Results

As the main goal of the study was to investigate group differences in print processing, the result section is focused on effects involving the Group factor.

3.1. Lexical decision

3.1.1. Behavioral results

Incorrect responses, outliers (mean RT ± 2.5 SD) and trials corresponding to contaminated epochs in the ERP data were excluded from the RTs analysis. Latencies and proportion of correct responses in each group for each task and stimulus type are displayed in Table 1. Analysis of the RTs revealed a significant main effect of Group ($F(1,40)=8.17$, $p<.01$, $\eta=.17$), with longer RTs for dyslexic (792 ms) than for expert readers (662 ms).

The Group*Lexicality interaction was marginal ($F(1,40)=3.21$, $p=.081$, $\eta=.07$). Analysis of the proportion of correct responses only revealed very marginal main effects of Group ($F(1,40)=3.09$, $p=.087$, $\eta=.07$) and Group*Lexicality interaction ($F(1,40)=3.24$, $p=.079$, $\eta=.07$).

Table 1. Mean latencies in ms (RTs) and proportion of correct responses in percentage (% CR) in each group for each stimulus type (standard deviations into brackets).

	Word RTs	Pseudoword RTs	Word % CR	Pseudoword % CR
Dyslexic group	738 (±180)	846 (±198)	89 (±5)	89 (±11)
Control Group	624 (±86)	699 (±105)	91 (±8)	95 (±6)

3.1.2. Waveform amplitude analyses

Figure 1A shows time points of significant amplitude differences between groups for the lexical decision task. Only differences with an alpha criterion of .02 and a minimum duration of 5 time-frames covering at least 4 clustered sites were considered. While the Group main effect did not reached significance, the analysis revealed a significant Group*Lexicality interaction. Different amplitudes were found between groups for words only between 240 and 250 ms on a cluster of 5 centro-posterior sites, with larger N2 amplitudes in expert compared to dyslexic readers.

Figure 1

3.1.3. Spatio-temporal analysis

Spatio-temporal segmentations were applied on the grand-average data of dyslexic and expert readers for each of the two stimulus type (i.e., words and pseudowords) from 80 ms to 400 ms after stimulus onset. The analysis revealed five different electrophysiological template maps (labelled A, B, C, D, E in Figure 1C) accounting for 91.36% of the variance. The two first periods of stable electrophysiological activity corresponding to the P1 component (Map A, from about 80 to 135 ms) and the beginning of the N2 component (Map B, from about 135 to 205 ms) were common to the two groups. Different electrophysiological spatial configurations were then observed between the two groups for words from about 205 ms (Map C) and irrespective of stimulus type from about 260 ms (Map D and E).

A fitting procedure was then applied to compare the map templates identified in the grand-averaged data with the individual ERP data in each group (i.e., dyslexic and control) and stimulus type (word and pseudoword) from 135 to 400 ms with maps B, C, D and E. Table 2 details the maps presence (in percentage individuals displaying it) and map duration in ms for each group and stimulus type. The only significant between group difference was observed on map E. This map displayed a larger presence for words in expert readers (95% of expert readers displayed this map for words) compared to dyslexic readers (only 52% of dyslexic readers displayed this map for words). No other effect or interaction involving the Group factor reached significance.

Table 2. For each topography, presence of the map in the individual ERPs in percentage (percentage of participants displaying the map) and average duration of the maps in ms for each group and stimulus type.

	Map presence (in %)				**Group difference**	
	Dyslexics		**Controls**		**Chi^2 W**	**Chi^2 PW**
	W	**PW**	**W**	**PW**		
Map B	81	90	67	86	1.11, p>.10	.23, p>.10
Map C	62	48	67	52	.10, p>.10	.10, p>.10
Map D	62	67	52	57	.39, p>.10	.40, p>.10
Map E	52	67	95	71	**9.98, p<.01 (Cohen d= .96)**	.11, p>.10
	Map duration (in ms)					
	Dyslexics		**Controls**		**Group effect**	**Group* Lexicality**
	W	**PW**	**W**	**PW**		
Map B	88	98	76	87	.43, p>.10	F<1, p>.10
Map C	48	42	46	37	F<1, p>.10	F<1, p>.10
Map D	60	65	45	59	F<1, p>.10	F<1, p>.10
Map F	60	51	88	73	2.70, p>.10	F<1, p>.10

W = words; PW = pseudowords

3.2. Reading aloud

3.2.1. Behavioral results

Latencies and proportion of correct responses in each group for each stimulus type are displayed in Table 3. Analysis of the RTs revealed a significant main effect of Group ($F(1,40)=17.11$, $p<.001$, η=.30), with longer RTs for dyslexic (711 ms) than for expert readers (579 ms). Of importance, the Group*Lexicality interaction ($F(1,40)=9.1$, $p<.01$, η=.19) was significant, with longer RTs for pseudowords compared to words in both groups. Post-hoc (Bonferroni correction) revealed that this lexicality effect was stronger in dyslexic (97 ms; p<.0001) compared to expert readers (45 ms; p<.01).

Concerning the proportion of correct responses, the main effect of Group was significant (F(1,40)=12.53, p<.01, η=.24), with a lower percentage of correct responses for dyslexic (85%) than for expert readers (90%). The Group*Lexicality interaction ($F(1,40)=22.25$, $p<.001$, η=.36) was significant, with a lower number of correct responses for pseudowords compared to words in both groups. Post-hoc (Bonferroni corrected) revealed that this lexicality effect was stronger in dyslexic (12%; p<.0001) compared to expert readers (4%; p=.03).

Table 3. Mean latencies in ms (RTs) and proportion of correct responses in percentage (% CR) in each group for each stimulus type (standard deviations into brackets).

	Word RTs	Pseudoword RTs	Word % CR	Pseudoword % CR
Dyslexic group	662 (±100)	759 (±152)	91 (±3)	79 (±7)
Control Group	556 (±69)	601 (±91)	92 (±5)	88 (±6)

3.2.2. Waveform Amplitude analyses

Figure 2A shows time points of significant amplitude differences between groups for the reading aloud task. Only difference with an alpha criterion of .02 and a minimum duration of 5 time-frames covering at least 4 clustered sites were considered. The main effect of Group was significant. Reduced ERP amplitudes were observed in dyslexic compared to expert readers at three time intervals: a) between 105 and 125 ms following stimulus onset on a cluster of 5 central sites; b) between 175 and 195 ms on a cluster of 6 to 8 left posterior sites (i.e., corresponding to the N2 time interval); and c) between 280 to 310 ms on a cluster of 4 left central sites (i.e., corresponding to the N320 time interval). The Group*Lexicality interaction did not reached significance.

Figure 2

3.2.3. Spatio-temporal analysis

Spatio-temporal segmentations were applied on the grand-average data of dyslexic and expert readers for each of the two stimulus type (i.e., words and pseudowords) from 80 ms to 400 ms after stimulus onset. The analysis revealed six different electrophysiological template maps (labelled A', B', C', D', E', F', in Figure 2C) accounting for 95.75% of the variance. The first period of stable electrophysiological activity corresponding to the P1 component (Map A', from 80 to 135 ms) was common to the two groups. Different electrophysiological spatial configurations were then observed between the two groups for both words and pseudowords from the N2 time interval to the end of the analyzed interval (i.e., from about 135 to 400 ms corresponding to maps B', C', D', E' and F'). A fitting procedure was then applied to compare the map templates identified in the grand-averaged data with the individual ERP data in each group (i.e., dyslexic and control) and stimulus type (i.e., words and pseudowords) from 135 to 400 ms with maps B', C', D', E' and F'. Table 4 details the maps presence in percentage and map duration in ms for each group and stimulus type. Statistical analysis performed on maps presence and duration revealed that maps B', D' and

F’ appeared to characterize dyslexics more than expert readers on pseudowords (map B’), on words (map D’) or on both words and pseudowords (map F’). Map E’ appeared to be more predominant in expert than in dyslexic readers as revealed by map presence (on words data) and map duration.

Table 4. For each topography, presence of the map in the individual ERPs in percentage (of participants displaying the map) and average duration of the map in ms for each group and stimulus type.

	Map presence (in %)				**Group difference**	
	Dyslexics		**Controls**		**Chi^2 W**	**Chi^2 PW**
	W	**PW**	**W**	**PW**		
Map B’	48	48	33	14	.89, p>.10	**5.46,p=.019 (Cohen d=.71)**
Map C’	71	81	71	90	/	.78, p>.10
Map D’	67	67	29	43	**6.11,p=.013 (Cohen d=.75)**	2.40, p>.10
Map E’	48	71	81	81	**5.08,p=.024 (Cohen d=.69)**	.53, p>.10
Map F’	71	62	33	29	**6.11,p=.013 (Cohen d=.75)**	**4.71,p=.030 (Cohen d=.66)**

	Map duration (in ms)					
	Dyslexics		**Controls**		**Group effect**	**Group* Lexicality**
	W	**PW**	**W**	**PW**		
Map B’	23	28	20	9	1.75, p>.10	2.63, p>.10
Map C’	53	68	67	78	F<1, p>.10	F<1, p>.10
Map D’	57	54	25	36	2.48, p>.10	1.19, p>.10
Map E’	57	66	114	119	**7.44, p<.01 (η=.16)**	F<1, p>.10
Map F’	67	39	30	14	**5.89,p<.02 (η=.13)**	F<1, p>.10

W = words; PW = pseudowords;

4. Discussion

The main findings of the present study revealed that the electrophysiological correlates of dyslexia in print processing vary both in timing and in nature according to the task requirements, here lexical decision and reading aloud. As discussed in the introduction, lexical decision has been widely used to investigate print processing in dyslexia and has mainly been associated to orthographic processes, whereas reading aloud, despite being more demanding on phonological processing and closer to reading in real life, has virtually not been used to compare expert and dyslexic readers in ERP studies.

4.1. Lexical decision: impairment in lexical access?

Dyslexic readers were globally slower to perform the lexical decision task compared to expert readers, irrespective of the kind of stimuli, supporting their difficulty in performing a visual word recognition task. Amplitude waveform analysis revealed reduced amplitudes at the end of the N2 interval in dyslexic compared to expert readers at posterior central sites. This between group difference was limited to word stimuli while it did not reach significance for pseudowords. This inter-group difference was observed later and at different sites than in previous ERP studies (Araújo et al., 2012; Dujardin et al., 2011; Mahé et al., 2012; 2013; Maurer et al., 2007; Shaul et al., 2012), where it was reported at about 170/200 ms and on left posterior sites. One might be surprised by the absence of larger between group differences on amplitudes at left posterior sites. It should be noted that while most of previous studies were focused on an interaction between the group and a specific effect on the N2 amplitude (e.g., a difference of print sensitivity or lexicality effect), the present experiment was more focused on between group differences on word and pseudoword processing. Second, in contrast to previous ERP studies, the present analysis was not a priori focused on a specific time interval or component and on specific sites. The analysis carried out on the entire time interval between stimulus presentation to 400 ms after at all sites required stricter statistical thresholds and criteria, which might explain the smaller effect in terms of number of channels and of time-points.

The spatio-temporal analysis revealed no between group differences in the N2 time interval. The between group differences observed on waveforms at centro-posterior sites in the present study seem to correspond to mere difference in amplitudes without shifts of differences on the global voltage distribution. This finding is especially informative relative to the reported alterations in dyslexic readers in the N2 sensitivity to print (Maurer et al., 2007; Mahé et al., 2012) or orthographic familiarity (Dujardin et al., 2012; Mahé et al., 2013; Shaul et al., 2012). Our pattern of data seems indeed to indicate that dyslexic readers would engage similar neural networks than expert readers at the N2 time interval. We may rather hypothesize the engagement of similar cognitive processes with a reduced efficiency in dyslexic readers. This hypothesis is supported by the later topographic differences observed between the two groups (presence of the last period of electrophysiological stability “E” on words). Indeed, the between group difference observed on map labelled “map E” was due to a specifically higher presence of this configuration at scalp for words compared to pseudowords in expert readers only. It might be hypothesized that in expert readers, after visual word form analysis, print processing would differ between words, whose orthographic form has been recognized, and pseudowords, which do not correspond to any stored lexical representation. In dyslexic readers, if the visual word form analysis is less efficient (Dujardin et al., 2012; Mahé et al., 2013; Shaul et al., 2012), familiar words may not have been well identified and require some additional processes. This could explain the group difference following the N2 time window and observed specifically for words. Concerning the lack of the between group difference for pseudowords, it should be noted that the context of the lexical decision task does not require a full processing of pseudowords. This might explain the lack of interaction between Group and Lexicality on the behavioral data.

4.2. Reading aloud: impaired phonological access from print?

In reading aloud, which requires explicit grapheme-to-phoneme conversion differently from lexical decision, the behavioural analysis revealed on both latencies and error rates stronger difficulties to process pseudowords than words in dyslexic readers relatively to the control group. This was especially visible in the accuracy data with very low scores for pseudowords in dyslexic readers. In the EEG data, between group differences were observed for both words and pseudowords. Differences were present on amplitudes between the two groups earlier than in the lexical decision task (i.e., around 100 ms after stimulus presentation). Reduced amplitudes were also observed in dyslexic compared to expert readers at the N2 time interval and between 280 and 310 ms on a cluster of 4 left central sites. This later time interval and the cluster corresponds to the N320 component, usually reported in experimental contexts or material putting a heavy weight on orthographic-to-phonological mapping and has been related to grapheme-to-phoneme conversion mechanisms in rhyme judgment (Bentin et al., 1999), silent reading (Simon et al., 2004) or lexical decision tasks involving pronounceable vs non pronounceable written strings (Simon et al., 2006). Our finding of reduced N320 amplitudes in dyslexic readers is consistent with the different N320 responses recorded in dyslexic readers relatively to expert readers in a perceptive decision task involving phonologically legal vs illegal stimuli (Araújo et al., 2012; 2015).

Concerning the spatio-temporal results, between group differences in reading aloud were also observed earlier than in lexical decision. First between group differences were observed as early as in the N2 time interval, with a stronger prevalence of the map labeled “map B’” for pseudowords in dyslexic compared to expert readers. After the N2 time interval, it should be noted that the between group differences observed in reading aloud appeared to be much larger than those observed at this interval in lexical decision, with completely different patterns of stable electric fields between the two groups from 225 ms to the end of the analyzed interval. This finding suggests that after initially close neural networks recruited for the processing of written strings in the two groups, a completely distinct pattern of print processing would be initiated according to reading skills after the N2 time interval. This pattern of data suggests the existence of a specific procedure in later processing stages of print processing (i.e., after the initial visual and orthographic analysis) in dyslexic readers. It should be noted that our dyslexic participants were all university students. We may thus hypothesize that they have developed alternative processing strategies during reading in order to compensate their difficulties. This alternative procedure observed during reading aloud may depend on the phonological abilities of participants. In support of a phonological hypothesis, the interval of between group differences covered the time window of the N320 component, with reduced amplitudes observed in dyslexic readers, which could be related to phonological deficits. Another argument in favor of a phonological interpretation of the inter-group differences observed in the spatio-temporal analysis is that those differences were not limited to words, but concerned both words and pseudowords.

In order to further investigate the link between this difference in topographic maps between control and expert readers in reading aloud and cognitive processes, correlation analyses were performed between specific cognitive processes and the duration of the maps D' and F' (observed specifically in dyslexic readers) and the duration of map E' (observed specifically in expert readers). The cognitive processes considered correspond to reading predictors measured during the initial participant screening: a metaphonology composite score (i.e., average of scores/RTs for phoneme deletion and spoonerisms), a RAN composite score (i.e., average of scores/RTs for letter and picture naming) and a visual attention span score (i.e., average of global and partial report scores). As displayed in Table 5, a significant correlation was found between the duration of Map F' for pseudowords and the metaphonology composite score ($r = -0.41$, $p<.01$). This pattern of negative correlation indicates that poorer phonological abilities are related to a longer duration of map F', suggesting a link between this map and the phonological deficits of dyslexic readers. In conclusion, the core phonological deficits reported in dyslexic readers (Blomert, 2010; Ramus & Szenkovits, 2008) seems to affect reading aloud processes with the engagement of different cognitive processes in dyslexic readers, at a time interval following the initial visual and orthographic analysis of written strings. A correlation was also found between the duration of map E’ for pseudowords (specifically observed in expert readers) and the visual span score (r = 0.48, p<.01), indicating that a longer duration of the map was related to better visual span abilities. This supports the view of alternative processing strategies, linked to different cognitive processes, between the two groups during reading aloud.

Table 5. Results of the correlations (r value of Pearson correlations, N=40) analysis between the duration of Map D’, F’ and E’ and the composite scores of metaphonology, RAN and visual attention span.

	Metaphonology score	RAN score	Visual span score
Maps observed in dyslexic readers			
Map D’ duration words	-0.17	-0.10	-0.31
Map D’ duration pseudowords	-0.05	-0.01	-0.21
Map F’ duration words	-0.29	-0.26	-0.14
Map F’ duration pseudowords	**-0.41 (p<.01)**	-0.29	-0.35
Map observed in expert readers			
Map E’ duration words	0.22	0.22	0.35
Map E’ duration pseudowords	0.27	0.20	**0.48 (p<.01)**

4.3. Neurophysiological specificities in print processing in developmental dyslexia: lexical decision vs. reading aloud

In a first experiment (Mahé et al., 2015), we revealed very early print processing differences between lexical decision and reading aloud (i.e., from about 180 ms at the N2 time interval) in adult expert readers. This pattern of data suggested that only low-level visual processes were shared by the two tasks. Specifically, a predominance of orthographic word form processing was only observed in lexical decision. The present findings reveal that in addition to initiate different processing stages during print processing, the two tasks reveal different patterns of divergences in developmental dyslexia. In lexical decision, a task focused on the fast and automatic recognition of familiar visual word forms, similar neurophysiological mechanisms seem to be involved in early stages of print processing in dyslexic and in expert readers. The between group difference observed after the N2 time interval may suggest a sub-efficient visual word form processing in dyslexia. In contrast, no apparent phonological deficits appeared in this context as no inter-group differences were observed on pseudowords. In reading aloud, when the context of print processing explicitly requires grapheme-to-phoneme conversion, earlier between group differences were observed compared to lexical decision, at around 100 ms in the amplitude waveform analysis. Of importance, the use of spatio-temporal segmentations revealed the involvement of completely different neural networks in print processing between expert and dyslexic readers after the N2 time window. This pattern of data suggests the use of an alternative procedure of print processing after the initial orthographic analysis of the written strings in dyslexic readers. Between group differences did not vary according to the stimulus type, suggesting that specific lexical processes were not the matter. The timing of the inter-group difference as well as the pattern of correlations observed seem to indicate that the alternative procedure of print processing observed in dyslexic readers during reading aloud could be related to their core phonological deficits. To our knowledge, this is the first ERP experiments comparing print processing in dyslexic and expert readers during a reading aloud task. This context seems particularly promising to further investigate the nature of phonological deficits during print processing in developmental dyslexia, and more specifically their difficulty to access phonological representations from print.

4.4. Conclusion

This study aimed at describing the electrophysiological correlates of print processing in developmental dyslexia in the known context of lexical decision and in the under-investigated context of reading aloud with both amplitude waveform analyses and spatio-temporal segmentations. ERP divergences of different nature and at different time windows were observed between dyslexic and expert readers depending on the task. Taken together it seems that depending on the core cognitive processes required by the tasks, each context allows to highlight different specificities in the time course of print processing in dyslexic readers. The lexical decision task appears to be better suited to assess lexical access while reading aloud appears to be better suited to assess phonological processes and impairments. It is especially interesting to observe that only the most demanding context relatively to phonological processes (i.e., the reading aloud task) implicates different strategies of print processing between the two groups. As lexical decision has dominated electrophysiological investigations comparing expert and dyslexic readers so far the present pattern of results calls for the use of a multi-task approach in future research or to adjust the experimental paradigm to the specific processes of interest. It should be noted that the present findings are observed in a specific population of dyslexic readers (i.e., university students). It would be interesting to extend these first results in a population of dyslexic readers who have not followed university studies. In addition, the investigation of dyslexic children could allow to get a better understanding of the developmental course of the phonological versus lexical/orthographic deficits.

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Figures

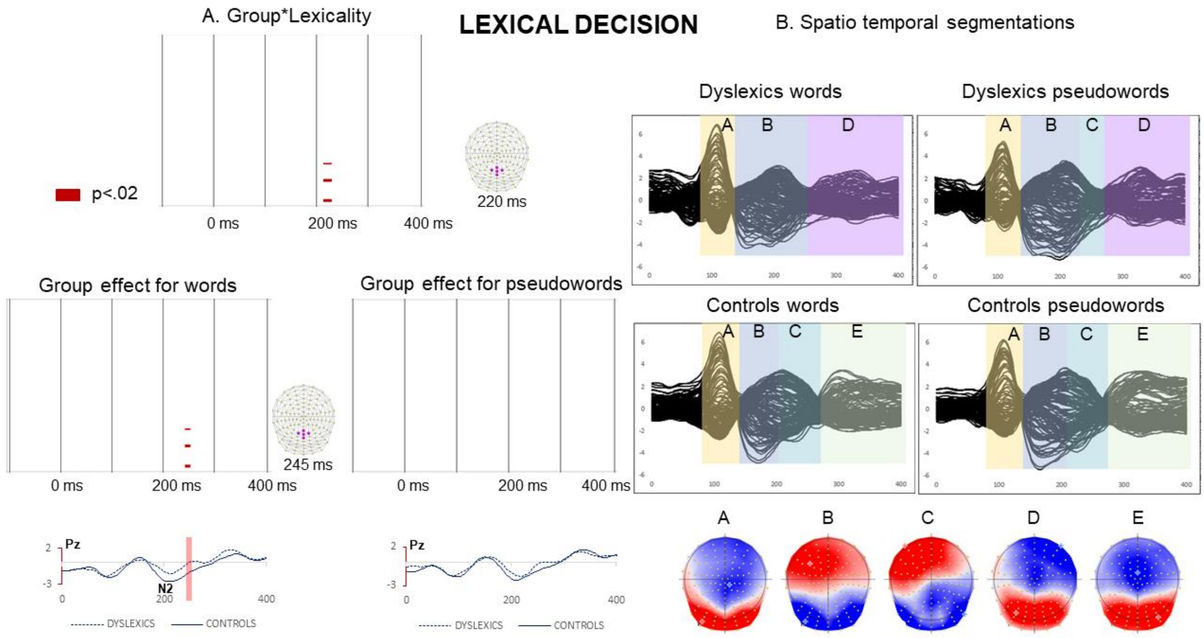

Figure 1A. Significant differences on ERP waveform amplitudes on each electrode (Y axes) and time point (X axes) between dyslexic and expert readers for words and pseudowords and interaction between stimulus type and group. Differences over at least four clustered electrodes and 5 consecutive time frames (10 ms), with an alpha criterion of .02 are displayed in red. The electrode sites yielding significant differences between the two groups at 240-250 ms and examples of waveforms (Pz) are displayed below**Figure 1B.** Grand average ERPs (128 electrodes) for each group (dyslexics on the top and controls on the bottom) and each stimulus type (words on the left and pseudowords on the right) and temporal distribution of the topographic maps revealed by the spatio-temporal segmentation analysis. Colors illustrate the time-window of each period of topographic stability. Corresponding map templates are displayed below.

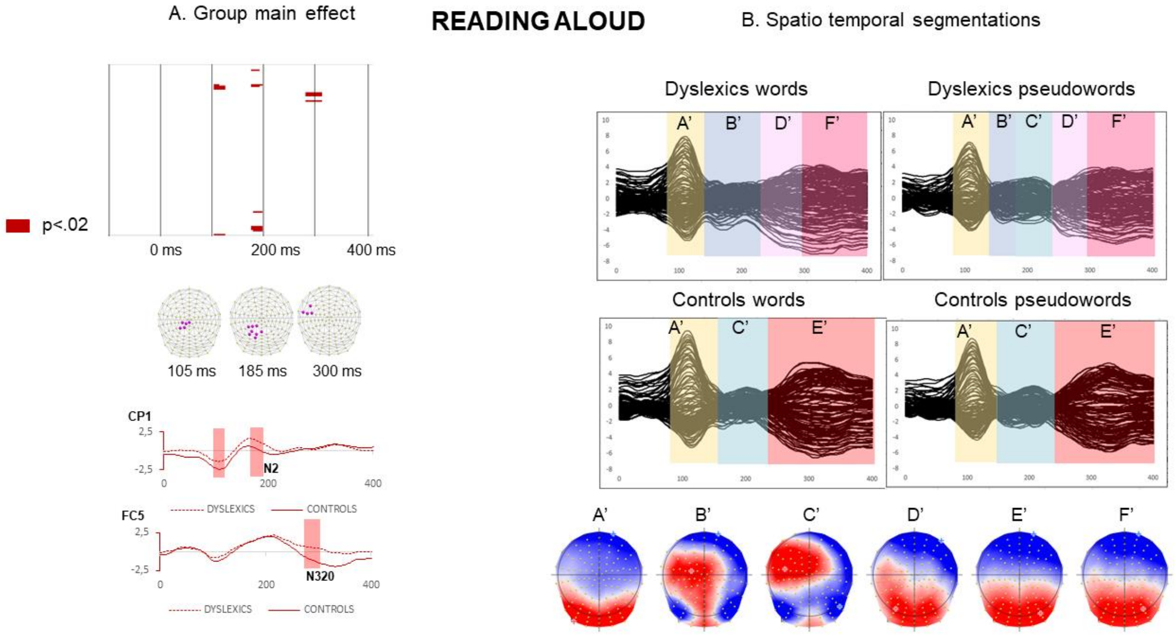

Figure 2A. Significant differences on ERP waveform amplitude on each electrode (Y axes) and time point (X axes) between dyslexic and expert readers. Only differences over at least four clustered electrodes and 5 consecutive time frames, with an alpha criterion of .02 are displayed in red. The electrode sites yielding significant differences between the two groups at 105-125 ms, 175-195 ms, and 280-310 ms and examples of waveforms (CP1, FC5) are displayed below . **Figure 2B.** Grand average ERPs (128 electrodes) for each group (dyslexics on the top and controls on the bottom) and each stimulus type (words on the left and pseudowords on the right) and temporal distribution of the topographic maps revealed by the spatio-temporal segmentation analysis in each data. Colors illustrate the time-window of each period of topographic stability. Corresponding map templates are displayed below.

Appendix

Appendix A. Characteristics of the word material.

	Words-List 1	Words-List 2	t-value
Number of letters	5.6 (4-8)	5.9 (4-8)	-1.6 ^{ns}
Number of phonemes	4.4 (2-7)	4.5 (2-7)	-0.2 ^{ns}
Number of syllables	1.7 (1-2)	1.6 (1-2)	-1 ^{ns}
Lexical frequency	33.6 (± 98.8)	37.2 (± 73.8)	-0.4 ^{ns}
Bigram frequency (per million)	8120.5 (± 3257)	8552 (± 3287.9)	-1 ^{ns}
Number of orthographic neighbors	2.2 (± 2.6)	1.8 (± 2.1)	1.1 ^{ns}
Number of phonological neighbors	7.2 (± 8.5)	6.6 (± 8)	0.6 ^{ns}
First syllable frequency (per million)	427.4 (± 898.6)	559.7 (± 1412.5)	-0.9 ^{ns}
Second syllable frequency (per million)	300.3 (± 1121.7)	189.5 (± 652.5)	0.7 ^{ns}

Stimulus type difference (t-test): *p*> .10 on all measures.

Appendix B. Characteristics of the pseudoword material.

	Pseudowords-List 1	Pseudowords-List 2	t-value
Bigram frequency (per million)	7703.9 (± 2941)	8184.9 (± 2896)	-1.3 ^{ns}
Number of orthographic neighbors	2 (± 2.9)	2.3 (± 3.7)	-0.6 ^{ns}
Number of phonological neighbors	5.6 (± 7.9)	6.6 (± 9.1)	-0.9 ^{ns}
First syllable frequency (per million)	487.2 (± 1217.3)	526.2 (± 1364.4)	-0.2 ^{ns}
Second syllable frequency (per million)	100.1 (± 220.1)	82.4 (± 249.8)	0.1^{ns}

Stimulus type difference (t-test): *p*> .10 on all measures.