



HAL
open science

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

Gwendoline Mahe, Cécile Pont, Pascal Zesiger, Marina Laganaro

► To cite this version:

Gwendoline Mahe, Cécile Pont, Pascal Zesiger, Marina Laganaro. The electrophysiological correlates of developmental dyslexia: New insights from lexical decision and reading aloud in adults. *Neuropsychologia*, 2018, *Neuropsychologia*, 121, pp.19-27. 10.1016/j.neuropsychologia.2018.10.025 . hal-03667535

HAL Id: hal-03667535

<https://hal.univ-lille.fr/hal-03667535>

Submitted on 13 May 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

3
4 Gwendoline Mahé ^a, Cécile Pont ^b, Pascal Zesiger ^b and Marina Laganaro ^b

5
6 ^a SCALab (UMR CNRS 9193), University of Lille, Domaine Universitaire du Pont de Bois,
7 BP60159, 59653 Villeneuve d'Ascq, France.

8 ^b FPSE, University of Geneva, 40 Bd Pont d'Arve, CH-1211 Genève 4, Switzerland.

9
10 * Corresponding author. Address: SCALab (UMR CNRES 9193), University of Lille,
11 Domaine Universitaire du Pont de Bois, BP60159, 59653 Villeneuve d'Ascq, France.

12 E-mail address: gwendoline.mahe@univ-lille.fr

13 Tel. 00 33 (0)3 20 41 69 89

14
15 Accepted version. Neuropsychologia.

1 Abstract

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

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

23

24

25

26

1 **1. Introduction**

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

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

4 1.1. Developmental dyslexia: impaired visual word recognition

5 In typical readers, with reading practice, a fast and parallel processing of familiar words
6 emerges, as supported by the disappearance of the word length effect several years after the
7 beginning of reading instruction (Zoccolotti, de Luca, di Pace, Gasperini, Judica, & Spinelli,
8 2005). In contrast, in dyslexic readers, this word length effect persists, suggesting a lack of
9 automatization of familiar words processing in this population. This lack of fast and parallel
10 processing of print has been supported by EEG data investigating the patterns of the N170
11 component specialization in this population using visual or orthographic decision tasks. Event
12 related potential (ERP) studies have associated the left N170 component (or N1/N2), which
13 peaks at around 200 ms at occipito-temporal sites, with the expert processing of print.
14 Experimental data have shown larger left N170 amplitude for wordlike stimuli compared to
15 visual non-orthographic stimuli such as symbol strings in adult expert readers (Brem, Bucher,
16 Halder, Summers, Dietrich, Martin et al., 2006; Maurer, Brem, Bucher, & Brandeis, 2005).
17 This tuning for print has been reported to be lacking in both dyslexic children using
18 immediate repetition detection (Maurer, Brem, Bucher, Kranz, Benz, Steinhausen, et al.,
19 2007) or letter/symbol decision task (Araújo, Bramão, Faísca, Magnus Petersson & Reis,
20 2012) and dyslexic adults using lexical decision tasks (Mahé, Bonnefond, Gavens, Dufour, &
21 Doignon-Camus, 2012; Mahé, Bonnefond, & Doignon-Camus, 2013). Lexical decision
22 experiments have also revealed an impaired fast lexical access in dyslexic adults, with a lack
23 (Mahé et al., 2013; Shaul, Arzouan, & Goldstein, 2012) or reverse (Dujardin, Etienne,
24 Contentin, Bernard, Largy, Mellier, et al., 2012) lexicality effect on the N170 (i.e., amplitude
25 difference between words and pseudowords) compared to expert readers. Taken together,

1 these data suggest that in the context of visual word recognition, dyslexic readers present
2 impairments in the early differentiation between verbal and nonverbal visual stimuli, and
3 between familiar and unfamiliar orthographic forms. This pattern of data is in line with brain
4 imaging studies describing in dyslexic readers an impaired specialization for print of specific
5 brain areas with reading acquisition (Paulesu, Demonet, Fazio, McCrory, Chanoine,
6 Brunswick, et al., 2001). However, it should be noted that the ERP studies described above
7 were limited to waveform amplitude analyses, which can hardly inform on whether different
8 underlying brain processes are involved. The use of spatio-temporal analyses would allow to
9 go deeper in the interpretation of the deficits in developmental dyslexia. Indeed, topographic
10 analyses allow to divide the ERP signal into periods of stable or quasi-stable global electric
11 fields at scalp (or microstates), likely to correspond to particular periods in mental
12 information processing (Changeux & Michel, 2004; Koukou & Lehman, 1987; Lehman, Strik,
13 Henggeler, Koenig, & Koukou, 1988). Spatio-temporal segmentations would thus allow to
14 determine whether the differences observed between expert and dyslexic readers are related to
15 the recruitment of different neural networks between the two groups. This would be indicative
16 of alternative processing strategies in dyslexic compared to expert readers.

17 1.2. Developmental dyslexia: the phonological deficit theory

18 The phonological mapping theory has linked the impaired specialization for print
19 observed in developmental dyslexia to their core phonological deficits (Maurer &
20 McCandliss, 2007; McCandliss & Noble, 2003). This theory postulates that decoding ability
21 affects the gradual specialization of neural networks for print processing during the early
22 years of reading. In this way, the impaired brain specialization for print described in dyslexic
23 readers would be a consequence of their core phonological deficits. More precisely, the
24 currently most established causal hypothesis of dyslexia identifies a deficit in the access to
25 phonological representations from print (Blomert, 2010; Ramus & Szenkovits, 2008). In

1 support, differences between expert and dyslexic readers have been reported on specific ERP
2 components related to phonological analysis such as the N320 component. This component
3 has been related to grapheme-to-phoneme conversion, supported by its larger amplitudes at
4 left central sites in response to phonologically legal (e.g., words, pseudowords) compared to
5 phonologically illegal stimuli (e.g., pseudoletters strings) in rhyme judgment (Bentin,
6 Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999), silent reading (Simon, Bernard,
7 Largy, Lalonde, & Rebaï, 2004) or lexical decision tasks (Simon, Bernard, Lalonde, & Rebaï,
8 2006). In developmental dyslexia, an impairment in the N320 response classically observed in
9 expert readers (i.e., larger N320 left amplitudes for phonologically legal vs. illegal stimuli)
10 has been reported in both dyslexic children (Araújo et al., 2012) and adults (Araújo, Faísca,
11 Bramão, Reis, & Peterson, 2015) in letter/symbol decision tasks. This pattern of data has been
12 taken as an evidence of impairments in later stages of phonological analysis. In support,
13 impaired responses have also been observed in dyslexic readers at other late ERP components
14 which have been related to phonological processing (Hasko, Groth, Bruder, Bartling, &
15 Schulte-Körne, 2013; Savill & Thierry, 2012). Taken together, all these ERP findings provide
16 further support for the phonological deficit theory of developmental dyslexia.

17 1.3. Developmental dyslexia research: the interest of the reading aloud task

18 Altogether, ERP experiments investigating the time course of print processing in
19 developmental dyslexia support an impaired specialization for print in relation to
20 phonological deficits in this population. It should be noted that such results derive from
21 decisional tasks focused on different linguistic aspects: perceptual for letter decision,
22 orthographic for lexical decision, phonological for phonological decision, or semantic for
23 semantic decision. To our knowledge, no data is currently available concerning the
24 neurophysiological differences in print processing between dyslexic and expert readers in the
25 context of a reading task (either silent or aloud). This appears surprising, especially in a

1 population likely characterized by core phonological deficits and considering the behavioral
2 studies highlighting the strongest sensitivity to phonological decoding of the reading aloud
3 tasks relative to the lexical decision tasks (Ferrand, Brysbaert, Keuleers, New, Bonin, Méot, et
4 al., 2011; Katz, Brancazio, Irwin, Katz, Magnuson, & Whalen, 2012). A recent meta-analysis
5 has considered behavioral studies performed with dyslexic children based on lexical decision
6 and reading aloud (Zoccoloti, De Luca, Di Filippo, Marinelli, & Spinelli, 2017). The authors
7 support the idea that the reading task is a determinant tool for the understanding of print
8 processing in developmental dyslexia. This is fully in line with the concept of functional
9 overlap introduced by Grainger & Jacobs (1996), which stipulates that the combination of
10 different experimental contexts (e.g., lexical decision, reading aloud, perceptual
11 identification) is crucial to understand the cognitive processes involved during print
12 processing and to improve the cognitive models of print processing. Each experimental task
13 would indeed be biased in favor of specific processing stages (Balota & Yap, 2006). The
14 lexical decision task puts a heavy weight on orthographic analysis while it does not explicitly
15 require associating the result of the orthographic analysis to a specific phonological output.
16 Additionally, this task implies an explicit choice between two alternatives. The reading aloud
17 task also involves an orthographic analysis but the focus is on the establishment of a precise
18 correspondence between the orthographic and the phonological forms of the word. An
19 implicit choice among thousands of alternatives is requested to perform the task. In order to
20 determine whether these task specificities are related to differences in the processing stages of
21 print processing, Mahé, Zesiger and Laganaro (2015) have compared the time course of print
22 processing between lexical decision and reading aloud in adult expert readers. Results
23 revealed a completely distinct time course of print processing between the two tasks from
24 about 140 ms after stimulus presentation, i.e., as early as the N170 component, with a
25 predominance of orthographic word form analysis in the lexical decision task only. As the two

1 tasks imply different processes, one might hypothesize that different patterns of print
2 processing impairments would emerge in dyslexic readers in the two tasks. Furthermore,
3 given the tasks properties, an approach combining both lexical decision and reading aloud
4 appears to be especially relevant to assess both impairment in visual word form analysis and
5 in phonological processes in dyslexia.

6 1.4. Aim of the present study

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

16 2. Method

17 2.1. Participants

18 The study was conducted at Geneva and Lille universities, with exactly the same
19 experimental procedures and the same recording material. Twenty-one university students
20 with a diagnosis of developmental dyslexia (6 men, mean age 22.6 years, \pm 4.4 years, 7 from
21 Geneva) and 21 age matched controls (4 men, mean age 21.2, \pm 2.3 years, 8 from Geneva)
22 took part in the experiment. All were native French speakers and right-handed as determined
23 by the Edinburgh Handedness Scales (Oldfield, 1971; mean lateralization quotient index
24 range: 85%; range: 60–100%) with normal or corrected-to-normal vision. All dyslexic

1 participants have been diagnosed by a speech and language therapist (mean age of diagnosis:
2 7.4 years; range 5 to 14 years) and have completed several years of remediation training
3 (mean 6 years; range 0.5 to 13 years), with no current remediation. Apart four dyslexic
4 participants who had also a diagnosis of dysorthographia, they reported no other
5 neurodevelopmental disorders (e.g., dysphasia, or attention deficit-hyperactivity disorder). All
6 participants gave their written informed consent and the study protocol was approved by the
7 local ethics committee.

8

9 Assessment of reading and other cognitive functions

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

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

16 Phonological skills were evaluated through phonological awareness tasks (i.e., phoneme
17 deletion and spoonerisms from the ECLA 16+; Gola-Asmussen et al., 2011) and rapid picture
18 and letter naming (RAN) taken respectively from the Evalad battery (George & Pech-Georgel,
19 2011) and the ECLA 16+ battery (Gola-Asmussen et al., 2011). Visuo-spatial attention skills
20 were evaluated with global and partial visual span tasks from the Evadys battery (Valdois,
21 Guinet, & Embs, 2014).

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

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

4 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

5

6 2.2. Material

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

10 2.3. Procedure

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

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

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

11 2.4. ERP recording and analysis

12 2.4.1. EEG acquisition and Pre-Analyses

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

16 Offline, ERPs were then bandpass-filtered to 0.2–30 Hz and notch-filtered to 50 Hz
17 and reaveraged to average references. Averaging was computed with epochs (i.e., specific
18 time windows extracted from the continuous EEG signal) of 500 ms starting 100 ms before to
19 400 ms after stimulus onset using the Cartool software (Brunet, Murray, & Michel, 2011).
20 Epochs contaminated by eye blinking, movements or other noise were rejected and excluded
21 from averaging after visual inspection. In addition, only trials with correct responses and valid
22 RTs were retained. As a result, a minimum of 55 averaged trials per participant in each
23 condition and task entered the ERP analyses (dyslexics: 55-114 epochs [mean=93] in lexical
24 decision; 64-112 epochs [mean=88] in reading aloud; controls: 61-116 epochs [mean=99] in
25 lexical decision; 66-113 epochs [mean=98] in reading aloud). Bad channels (i.e., electrodes

1 with artifacts or missing signal) were interpolated using 3-D splines interpolation (Perrin,
2 Pernier, Bertrand, Giard, & Echallier, 1987). This procedure allows to reconstruct a missing
3 or poor EEG signal from a specific electrode by combining signals from neighboring
4 electrodes. On average 9 channels were interpolated for each participant. The number of
5 averaged trials and interpolated electrodes did not differ between the two groups.

6 2.4.2. Waveform analyses

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

19 2.4.3. Global topographic ERP pattern analyses

20 Second, global topographic ERP pattern analyses were performed. The topographic analysis
21 consisted in clustering the ERP signal (from 80 to 400 ms after stimulus onset) into different
22 periods of stable or quasi-stable global electric fields, each assumed to correspond to
23 particular periods in mental information processing (Changeux & Michel, 2004; Koukou &
24 Lehmann, 1987; Lehman et al., 1998). The global topographic patterns further inform on the
25 nature of the between group differences: a) whether they are limited to a mere difference in

1 the strength of the electric field (i.e., only amplitude differences); b) whether different
2 neurophysiological mechanisms underlie print processing between the two groups, with
3 topographic differences; c) whether they rely on the involvement of similar
4 neurophysiological mechanisms engaged for a shorter/longer time-period, in the case of
5 similar microstates characterized by different durations or by shifts.

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

1 and the duration of each cluster map in each individual ERP, these measures being used then
2 for the statistical comparisons between groups and conditions. .

3 In order to analyze whether some maps were more representative of one group compared to
4 the other, the map presence and map duration in ms observed in each subject's data were used
5 for statistical analysis. Repeated measure ANOVAs were computed for each task on map
6 duration with the between subject factor Group and the within subject factor Lexicality.

7 Concerning map presence, Pearson chi square were applied to compare dyslexic and expert
8 readers on each condition.

9 3. Results

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

12 3.1. Lexical decision

13 3.1.1. Behavioral results

14 Incorrect responses, outliers (mean RT \pm 2.5 SD) and trials corresponding to contaminated
15 epochs in the ERP data were excluded from the RTs analysis. Latencies and proportion of
16 correct responses in each group for each task and stimulus type are displayed in Table 1.

17 Analysis of the RTs revealed a significant main effect of Group ($F(1,40)=8.17, p<.01, \eta=.17$),
18 with longer RTs for dyslexic (792 ms) than for expert readers (662 ms).

19 The Group*Lexicality interaction was marginal ($F(1,40)=3.21, p=.081, \eta=.07$). Analysis of
20 the proportion of correct responses only revealed very marginal main effects of Group
21 ($F(1,40)=3.09, p=.087, \eta=.07$) and Group*Lexicality interaction ($F(1,40)=3.24, p=.079,$
22 $\eta=.07$).

23

24

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

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

3

4 3.1.2. Waveform amplitude analyses

5 Figure 1A shows time points of significant amplitude differences between groups for
 6 the lexical decision task. Only differences with an alpha criterion of .02 and a minimum
 7 duration of 5 time-frames covering at least 4 clustered sites were considered. While the Group
 8 main effect did not reached significance, the analysis revealed a significant Group*Lexicality
 9 interaction. Different amplitudes were found between groups for words only between 240 and
 10 250 ms on a cluster of 5 centro-posterior sites, with larger N2 amplitudes in expert compared
 11 to dyslexic readers.

12 -----

13 Figure 1

14 -----

15 3.1.3. Spatio-temporal analysis

16 Spatio-temporal segmentations were applied on the grand-average data of dyslexic and expert
 17 readers for each of the two stimulus type (i.e., words and pseudowords) from 80 ms to 400 ms
 18 after stimulus onset. The analysis revealed five different electrophysiological template maps
 19 (labelled A, B, C, D, E in Figure 1C) accounting for 91.36% of the variance. The two first
 20 periods of stable electrophysiological activity corresponding to the P1 component (Map A,
 21 from about 80 to 135 ms) and the beginning of the N2 component (Map B, from about 135 to
 22 205 ms) were common to the two groups. Different electrophysiological spatial

1 configurations were then observed between the two groups for words from about 205 ms
 2 (Map C) and irrespective of stimulus type from about 260 ms (Map D and E).
 3 A fitting procedure was then applied to compare the map templates identified in the grand-
 4 averaged data with the individual ERP data in each group (i.e., dyslexic and control) and
 5 stimulus type (word and pseudoword) from 135 to 400 ms with maps B, C, D and E. Table 2
 6 details the maps presence (in percentage individuals displaying it) and map duration in ms for
 7 each group and stimulus type. The only significant between group difference was observed on
 8 map E. This map displayed a larger presence for words in expert readers (95% of expert
 9 readers displayed this map for words) compared to dyslexic readers (only 52% of dyslexic
 10 readers displayed this map for words). No other effect or interaction involving the Group
 11 factor reached significance.

12

13 Table 2. For each topography, presence of the map in the individual ERPs in percentage
 14 (percentage of participants displaying the map) and average duration of the maps in ms for
 15 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	.11, p>.10
					(Cohen d= .96)	
	Map duration (in ms)				Group effect	Group* Lexicality
	Dyslexics		Controls			
	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

16 W = words; PW = pseudowords

1 3.2. Reading aloud

2 3.2.1. Behavioral results

3 Latencies and proportion of correct responses in each group for each stimulus type are
4 displayed in Table 3. Analysis of the RTs revealed a significant main effect of Group
5 ($F(1,40)=17.11, p<.001, \eta=.30$), with longer RTs for dyslexic (711 ms) than for expert
6 readers (579 ms). Of importance, the Group*Lexicality interaction ($F(1,40)=9.1, p<.01,$
7 $\eta=.19$) was significant, with longer RTs for pseudowords compared to words in both groups.
8 Post-hoc (Bonferroni correction) revealed that this lexicality effect was stronger in dyslexic
9 (97 ms; $p<.0001$) compared to expert readers (45 ms; $p<.01$).

10 Concerning the proportion of correct responses, the main effect of Group was
11 significant ($F(1,40)=12.53, p<.01, \eta=.24$), with a lower percentage of correct responses for
12 dyslexic (85%) than for expert readers (90%). The Group*Lexicality interaction
13 ($F(1,40)=22.25, p<.001, \eta=.36$) was significant, with a lower number of correct responses for
14 pseudowords compared to words in both groups. Post-hoc (Bonferroni corrected) revealed
15 that this lexicality effect was stronger in dyslexic (12%; $p<.0001$) compared to expert readers
16 (4%; $p=.03$).

17

18 Table 3. Mean latencies in ms (RTs) and proportion of correct responses in percentage (%
19 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)

20

21 3.2.2. Waveform Amplitude analyses

22 Figure 2A shows time points of significant amplitude differences between groups for
23 the reading aloud task. Only difference with an alpha criterion of .02 and a minimum duration
24 of 5 time-frames covering at least 4 clustered sites were considered. The main effect of Group

1 was significant. Reduced ERP amplitudes were observed in dyslexic compared to expert
2 readers at three time intervals: a) between 105 and 125 ms following stimulus onset on a
3 cluster of 5 central sites; b) between 175 and 195 ms on a cluster of 6 to 8 left posterior sites
4 (i.e., corresponding to the N2 time interval); and c) between 280 to 310 ms on a cluster of 4
5 left central sites (i.e., corresponding to the N320 time interval). The Group*Lexicality
6 interaction did not reached significance.

7 -----

8 Figure 2

9 -----

10 3.2.3. Spatio-temporal analysis

11 Spatio-temporal segmentations were applied on the grand-average data of dyslexic and
12 expert readers for each of the two stimulus type (i.e., words and pseudowords) from 80 ms to
13 400 ms after stimulus onset. The analysis revealed six different electrophysiological template
14 maps (labelled A', B', C', D', E', F', in Figure 2C) accounting for 95.75% of the variance.
15 The first period of stable electrophysiological activity corresponding to the P1 component
16 (Map A', from 80 to 135 ms) was common to the two groups. Different electrophysiological
17 spatial configurations were then observed between the two groups for both words and
18 pseudowords from the N2 time interval to the end of the analyzed interval (i.e., from about
19 135 to 400 ms corresponding to maps B', C', D', E' and F'). A fitting procedure was then
20 applied to compare the map templates identified in the grand-averaged data with the
21 individual ERP data in each group (i.e., dyslexic and control) and stimulus type (i.e., words
22 and pseudowords) from 135 to 400 ms with maps B', C', D', E' and F'. Table 4 details the
23 maps presence in percentage and map duration in ms for each group and stimulus type.
24 Statistical analysis performed on maps presence and duration revealed that maps B', D' and

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

5

6 Table 4. For each topography, presence of the map in the individual ERPs in percentage (of
 7 participants displaying the map) and average duration of the map in ms for each group and
 8 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)				Group effect	Group* Lexicality
	Dyslexics		Controls			
	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 ($\eta=.16$)	F<1, p>.10
Map F'	67	39	30	14	5.89,p<.02 ($\eta=.13$)	F<1, p>.10

9 W = words; PW = pseudowords;

10 4. Discussion

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

8 4.1. Lexical decision: impairment in lexical access?

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

1 criteria, which might explain the smaller effect in terms of number of channels and of time-
2 points.

3 The spatio-temporal analysis revealed no between group differences in the N2 time interval.
4 The between group differences observed on waveforms at centro-posterior sites in the present
5 study seem to correspond to mere difference in amplitudes without shifts of differences on the
6 global voltage distribution. This finding is especially informative relative to the reported
7 alterations in dyslexic readers in the N2 sensitivity to print (Maurer et al., 2007; Mahé et al.,
8 2012) or orthographic familiarity (Dujardin et al., 2012; Mahé et al., 2013; Shaul et al., 2012).
9 Our pattern of data seems indeed to indicate that dyslexic readers would engage similar neural
10 networks than expert readers at the N2 time interval. We may rather hypothesize the
11 engagement of similar cognitive processes with a reduced efficiency in dyslexic readers. This
12 hypothesis is supported by the later topographic differences observed between the two groups
13 (presence of the last period of electrophysiological stability “E” on words). Indeed, the between
14 group difference observed on map labelled “map E” was due to a specifically higher presence
15 of this configuration at scalp for words compared to pseudowords in expert readers only. It
16 might be hypothesized that in expert readers, after visual word form analysis, print processing
17 would differ between words, whose orthographic form has been recognized, and pseudowords,
18 which do not correspond to any stored lexical representation. In dyslexic readers, if the visual
19 word form analysis is less efficient (Dujardin et al., 2012; Mahé et al., 2013; Shaul et al., 2012),
20 familiar words may not have been well identified and require some additional processes. This
21 could explain the group difference following the N2 time window and observed specifically for
22 words. Concerning the lack of the between group difference for pseudowords, it should be noted
23 that the context of the lexical decision task does not require a full processing of pseudowords.
24 This might explain the lack of interaction between Group and Lexicality on the behavioral data.

25 4.2. Reading aloud: impaired phonological access from print?

1 In reading aloud, which requires explicit grapheme-to-phoneme conversion differently
2 from lexical decision, the behavioural analysis revealed on both latencies and error rates
3 stronger difficulties to process pseudowords than words in dyslexic readers relatively to the
4 control group. This was especially visible in the accuracy data with very low scores for
5 pseudowords in dyslexic readers. In the EEG data, between group differences were observed
6 for both words and pseudowords. Differences were present on amplitudes between the two
7 groups earlier than in the lexical decision task (i.e., around 100 ms after stimulus presentation).
8 Reduced amplitudes were also observed in dyslexic compared to expert readers at the N2 time
9 interval and between 280 and 310 ms on a cluster of 4 left central sites. This later time interval
10 and the cluster corresponds to the N320 component, usually reported in experimental contexts
11 or material putting a heavy weight on orthographic-to-phonological mapping and has been
12 related to grapheme-to-phoneme conversion mechanisms in rhyme judgment (Bentin et al.,
13 1999), silent reading (Simon et al., 2004) or lexical decision tasks involving pronounceable vs
14 non pronounceable written strings (Simon et al., 2006). Our finding of reduced N320
15 amplitudes in dyslexic readers is consistent with the different N320 responses recorded in
16 dyslexic readers relatively to expert readers in a perceptive decision task involving
17 phonologically legal vs illegal stimuli (Araújo et al., 2012; 2015).

18 Concerning the spatio-temporal results, between group differences in reading aloud
19 were also observed earlier than in lexical decision. First between group differences were
20 observed as early as in the N2 time interval, with a stronger prevalence of the map labeled “map
21 B” for pseudowords in dyslexic compared to expert readers. After the N2 time interval, it
22 should be noted that the between group differences observed in reading aloud appeared to be
23 much larger than those observed at this interval in lexical decision, with completely different
24 patterns of stable electric fields between the two groups from 225 ms to the end of the analyzed
25 interval. This finding suggests that after initially close neural networks recruited for the

1 processing of written strings in the two groups, a completely distinct pattern of print processing
2 would be initiated according to reading skills after the N2 time interval. This pattern of data
3 suggests the existence of a specific procedure in later processing stages of print processing (i.e.,
4 after the initial visual and orthographic analysis) in dyslexic readers. It should be noted that our
5 dyslexic participants were all university students. We may thus hypothesize that they have
6 developed alternative processing strategies during reading in order to compensate their
7 difficulties. This alternative procedure observed during reading aloud may depend on the
8 phonological abilities of participants. In support of a phonological hypothesis, the interval of
9 between group differences covered the time window of the N320 component, with reduced
10 amplitudes observed in dyslexic readers, which could be related to phonological deficits.
11 Another argument in favor of a phonological interpretation of the inter-group differences
12 observed in the spatio-temporal analysis is that those differences were not limited to words, but
13 concerned both words and pseudowords.

14 In order to further investigate the link between this difference in topographic maps
15 between control and expert readers in reading aloud and cognitive processes, correlation
16 analyses were performed between specific cognitive processes and the duration of the maps D'
17 and F' (observed specifically in dyslexic readers) and the duration of map E' (observed
18 specifically in expert readers). The cognitive processes considered correspond to reading
19 predictors measured during the initial participant screening: a metaphonology composite score
20 (i.e., average of scores/RTs for phoneme deletion and spoonerisms), a RAN composite score
21 (i.e., average of scores/RTs for letter and picture naming) and a visual attention span score (i.e.,
22 average of global and partial report scores). As displayed in Table 5, a significant correlation
23 was found between the duration of Map F' for pseudowords and the metaphonology composite
24 score ($r = -0.41, p < .01$). This pattern of negative correlation indicates that poorer phonological
25 abilities are related to a longer duration of map F', suggesting a link between this map and the

1 phonological deficits of dyslexic readers. In conclusion, the core phonological deficits reported
 2 in dyslexic readers (Blomert, 2010; Ramus & Szenkovits, 2008) seems to affect reading aloud
 3 processes with the engagement of different cognitive processes in dyslexic readers, at a time
 4 interval following the initial visual and orthographic analysis of written strings. A correlation
 5 was also found between the duration of map E' for pseudowords (specifically observed in expert
 6 readers) and the visual span score ($r = 0.48, p < .01$), indicating that a longer duration of the map
 7 was related to better visual span abilities. This supports the view of alternative processing
 8 strategies, linked to different cognitive processes, between the two groups during reading aloud.

9 Table 5. Results of the correlations (r value of Pearson correlations, N=40) analysis between
 10 the duration of Map D', F' and E' and the composite scores of metaphonology, RAN and visual
 11 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)

12
 13 4.3. Neurophysiological specificities in print processing in developmental dyslexia: lexical
 14 decision vs. reading aloud

15 In a first experiment (Mahé et al., 2015), we revealed very early print processing
 16 differences between lexical decision and reading aloud (i.e., from about 180 ms at the N2 time
 17 interval) in adult expert readers. This pattern of data suggested that only low-level visual
 18 processes were shared by the two tasks. Specifically, a predominance of orthographic word

1 form processing was only observed in lexical decision. The present findings reveal that in
2 addition to initiate different processing stages during print processing, the two tasks reveal
3 different patterns of divergences in developmental dyslexia. In lexical decision, a task focused
4 on the fast and automatic recognition of familiar visual word forms, similar neurophysiological
5 mechanisms seem to be involved in early stages of print processing in dyslexic and in expert
6 readers. The between group difference observed after the N2 time interval may suggest a sub-
7 efficient visual word form processing in dyslexia. In contrast, no apparent phonological deficits
8 appeared in this context as no inter-group differences were observed on pseudowords. In
9 reading aloud, when the context of print processing explicitly requires grapheme-to-phoneme
10 conversion, earlier between group differences were observed compared to lexical decision, at
11 around 100 ms in the amplitude waveform analysis. Of importance, the use of spatio-temporal
12 segmentations revealed the involvement of completely different neural networks in print
13 processing between expert and dyslexic readers after the N2 time window. This pattern of data
14 suggests the use of an alternative procedure of print processing after the initial orthographic
15 analysis of the written strings in dyslexic readers. Between group differences did not vary
16 according to the stimulus type, suggesting that specific lexical processes were not the matter.
17 The timing of the inter-group difference as well as the pattern of correlations observed seem to
18 indicate that the alternative procedure of print processing observed in dyslexic readers during
19 reading aloud could be related to their core phonological deficits. To our knowledge, this is the
20 first ERP experiments comparing print processing in dyslexic and expert readers during a
21 reading aloud task. This context seems particularly promising to further investigate the nature
22 of phonological deficits during print processing in developmental dyslexia, and more
23 specifically their difficulty to access phonological representations from print.

24 4.4. Conclusion

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

20 Funding

21 This study was supported by the SNSF grant 1000014_149595, the French National Research
22 Agency (ANR-11-EQPX-0023) and also supported by European funds through the program
23 FEDER SCV-IrDIVE.

24

1 References

- 2 Aghababian, V., & Nazir, T. A. (2000). Developing normal reading skills: aspects of the visual
3 processes underlying word recognition. *Journal of Experimental Child Psychology*, *76*(2), 123–
4 150.
- 5 Araújo, S., Bramão, I., Faísca, L., Magnus Petersson, K., & Reis, A. (2012).
6 Electrophysiological correlates of impaired reading in dyslexic pre-adolescent children. *Brain*
7 *and Cognition*, *79*, 79–88.
- 8 Araújo, S., Faísca, L., Bramão, I., Reis, A., & Peterson, K. M. (2015). Lexical and sublexical
9 orthographic processing: An ERP study with skilled and dyslexic adult readers. *Brain and*
10 *Language*, *141*, 16–27.
- 11 Balota, D. A., & Yap, M. (2006). Attentional control and flexible lexical processing:
12 explorations of the magic moment of word recognition. In: Andrews, S. (Ed.), *From Inkmarks*
13 *to Ideas: Current Issues in Lexical Processing*. Psychology Press, New York, N.Y., pp. 229–
14 258.
- 15 Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP
16 manifestations of processing printed words at different psycholinguistic levels: time course
17 and scalp distribution. *Journal of Cognitive Neuroscience*, *11*(3), 235–260.
- 18 Blomert, L. (2010). The neural signature of orthographic-phonological binding in successful
19 and failing reading development. *NeuroImage* *57*:695–703.
- 20 Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., & Brandeis, D.
21 (2006). Evidence for developmental changes in the visual word processing network beyond
22 adolescence. *NeuroImage*, *29*, 822–837.
- 23 Brunet, D., Murray, M. M., Michel, C. M. (2011). Spatiotemporal analysis of multichannel
24 EEG: CARTOOL. *Computational Intelligence and Neuroscience*.

- 1 Changeux, J. P., & Michel, C. M. (2004). “Mechanisms of neural integration at the brain scale
2 level: the neuronal work space and microstate models”, in *Microcircuits: The Interface*
3 *between Neurons and Global Brain Function*, eds Grillner S. and Grabyel A.M.
4 (Cambridge,MA:TheMITPress):347–370.
- 5 Dujardin, T., Etienne, Y., Contentin, C., Bernard, C., Largy, P., Mellier, D., Lallonde, R., &
6 Rebaï, M. (2011). Behavioral performances in participants with phonological dyslexia and
7 different patterns on the N170 component. *Brain and Cognition*, 75, 91–100.
- 8 Ferrand, L., Brysbaert, M., Keuleers, E., New, B., Bonin, P., Méot, A., Augustinova, M., &
9 Pallier, C. (2011). Comparing word processing times in naming, lexical decision, and
10 progressive demasking: evidence from Chronolex. *Frontiers in Psychology*, 2, 306.
- 11 George, F., & Pech-Georgel, C. (2011). EVALAD: Evaluation du langage écrit et des
12 compétences transversales –Adolescents de 1^{ère} et de terminale ou adultes. De Boeck Supérieur.
- 13 Gola-Asmussen, C., Lequette, C., Pouget, G., Rouyer, C., & Zorman, M. (2011). ECLA 16+ :
14 Evaluation des compétences de lecture chez l’adulte de plus de 16 ans. Cogni-Sciences.
- 15 Grainger, J., & Jacobs, A. (1996). Orthographic processing in visual word recognition: a
16 multiple read-out model. *Psychological Review*, 103(3), 518–565.
- 17 Hasko, S., Groth, K., Bruder, J., Bartling, J., & Schulte-Körne, G. (2013). The time course of
18 reading in children with and without dyslexia: an ERP study. *Frontiers in Human*
19 *Neuroscience*, 7:570.
- 20 Katz, L., Brancazio, L., Irwin, J., Katz, S., Magnuson, J., & Whalen, D.H. (2012). What
21 lexical decision and naming tell us about reading. *Reading and Writing*, 25, 1259–1282.
- 22 Koukou, M., & Lehmann, D. (1987). An Information processing perspective of
23 psychophysiological measurements. *Journal of Psychophysiology*, 1:109–112.

1 Lehmann, D., Strik, W. K., Henggeler, B., Koenig, T., & Koukkou, M. (1998). Brain electric
2 microstates and momentary conscious mind states as building blocks of spontaneous thinking:
3 I. Visual imagery and abstract thoughts. *International Journal of Psychophysiology*, 29:1–11.

4 Lindgren, S. D., De Renzi, E., & Richman, L. C. (1985). Cross-national comparisons of
5 developmental dyslexia in Italy and the United States. *Child Development*, 56(6), 1404–1417.

6 Mahé, G., Bonnefond, A., & Doignon-Camus, N. (2013). Is the impaired N170 print tuning
7 specific to developmental dyslexia? A matched reading level study with poor readers and
8 dyslexics. *Brain and Language*, 127, 539–544.

9 Mahé, G., Bonnefond, A., Gavens, N., Dufour, A., & Doignon-Camus, N. (2012). Impaired
10 visual expertise for print in French adults with compensated dyslexia as shown by N170
11 tuning. *Neuropsychologia*, 50, 3200–3206.

12 Mahé, G., Zesiger, P., & Laganaro, M. (2015). Beyond the initial 140 ms, lexical decision and
13 reading aloud are different tasks : An ERP study with topographic analysis. *NeuroImage*, 122,
14 65–72.

15 Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological
16 specialization for letter strings. *Journal of Cognitive Neuroscience*, 17, 1532–1552.

17 Maurer, U., Brem, S., Bucher, K., Kranz, F., Benz, R., Steinhausen, H. C., & Brandeis, D.
18 (2007). Impaired tuning of a fast occipito-temporal response for print in dyslexic children
19 learning to read. *Brain*, 130, 3200–3210.

20 Maurer, U., & McCandliss, B. (2007). The development of visual expertise for words: the
21 contribution of electrophysiology. In: E. L. Grigorenko, A. J. Naples (Eds.), *Single-word
22 reading: biological and behavioural perspectives* (pp. 43–63). Mahwah, NJ: Lawrence
23 Erlbaum Associates.

1 McCandliss, B., & Noble, K. (2003). The development of reading impairment: A cognitive
2 neuroscience model. *Mental Retardation and Developmental Disabilities Research Reviews*,
3 9(3), 196–204.

4 Michel, C. M., Thut, G., Morand, S., Khateb, A., Pegna, A. J., & Grave de Peralta, R. (2001).
5 Electric source imaging of human brain functions. *Brain Research Reviews*, 36:108–118.

6 Murray, M. M., Brunet, D., & Michel, C. M. (2008). Topographic ERP analyses: a step-by-
7 step tutorial review. *Brain Topography*, 20:249–264.

8 New, B., Pallier, C., Ferrand, L., & Matos, R. (2001). Une base de données lexicales du
9 français contemporain sur internet: Lexique. *L'Année Psychologique* 101:447–462.

10 Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh inventory.
11 *Neuropsychologia*, 9:97–113.

12 Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1995). Segmentation of brain
13 electrical activity into microstates: Model estimation and validation. *IEEE Transaction on*
14 *Biomedical Engineering*, 42:658–665.

15 Paulesu, E., Demonet, J.F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., et al.
16 (2001). Dyslexia: cultural diversity and biological unity. *Science*, 291, 2165–2167.

17 Perrin, F., Pernier, J., Bertrand, O., Giard, M. H., & Echallier, J. F. (1987). Mapping of scalp
18 potentials by surface spline interpolation. *Electroencephalography and Clinical Neurophysiology*
19 66:75–81.

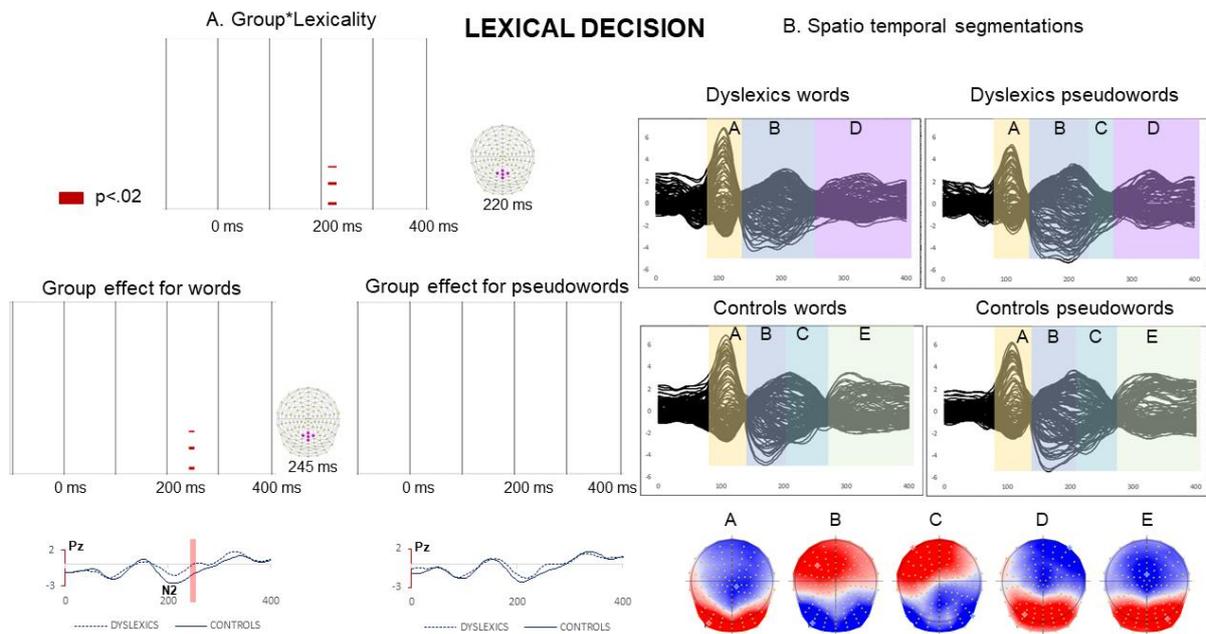
20 Protopapas, A. (2007). Check Vocal: A program to facilitate checking the accuracy and
21 response time of vocal responses from DMDX. *Behavioral Research Methods*, 39:859–862.

22 Ramus, F., & Szenkovits, G. (2008). What phonological deficit? *Quarterly Journal of*
23 *Experimental Psychology*, 61:129–41.

24 Raven, J., Raven, J. C., & Court, J. H. (1998). Advanced progressive matrices. Oxford:
25 Oxford Psychologists Press.

- 1 Savill, N. J., & Thierry, G. (2012). Decoding ability makes waves in reading: Deficient
2 interactions between attention and phonological analysis in developmental dyslexia.
3 *Neuropsychologia*, 50(7), 1553–1564.
- 4 Shaul, S., Arzouan, Y., & Goldstein, A. (2012). Brain activity while reading words and pseudo-
5 words: a comparison between dyslexic and fluent readers. *International Journal of*
6 *Psychophysiology*, 84, 270–276.
- 7 Simon, G., Bernard, C., Lalonde, R., & Rebaï, M. (2006). Orthographic transparency and
8 grapheme-phoneme conversion : An ERP study in Arabic and French readers. *Brain Research*,
9 141–152.
- 10 Simon, G., Bernard, C., Largy, P., Lalonde, R., & Rebaï, M. (2004). Chronometry of visual
11 word recognition during passive and lexical decision tasks: an ERP investigation.
12 *International Journal of Neuroscience*, 114(11), 1401–1432.
- 13 Valdois, S., Guinet, E., & Embs, J.-L. (2014). EVADYS : logiciel d'évaluation de l'empan
14 visuo-attentionnel (VA) chez l'enfant dyslexique. Ortho Editions.
- 15 World Health Organization. (2008). International statistical classification of diseases and
16 related health problems –Tenth revision (2nd edn). Geneva: World Health Organization.
- 17 Zoccolotti, P., de Luca, M., di Pace, E., Gasperini, F., Judica, A., & Spinelli, D. (2005). Word
18 length effect in early reading and in developmental dyslexia. *Brain & Language*, 93(3), 369–
19 373.
- 20 Zoccolotti, P., De Luca, M., Di Filippo, G., Marinelli, C., & Spinelli, D. (2017). Reading and
21 lexical-decision tasks generate different patterns of individual variability as a function of
22 condition difficulty. *Psychonomic Bulletin and Review* (in press).

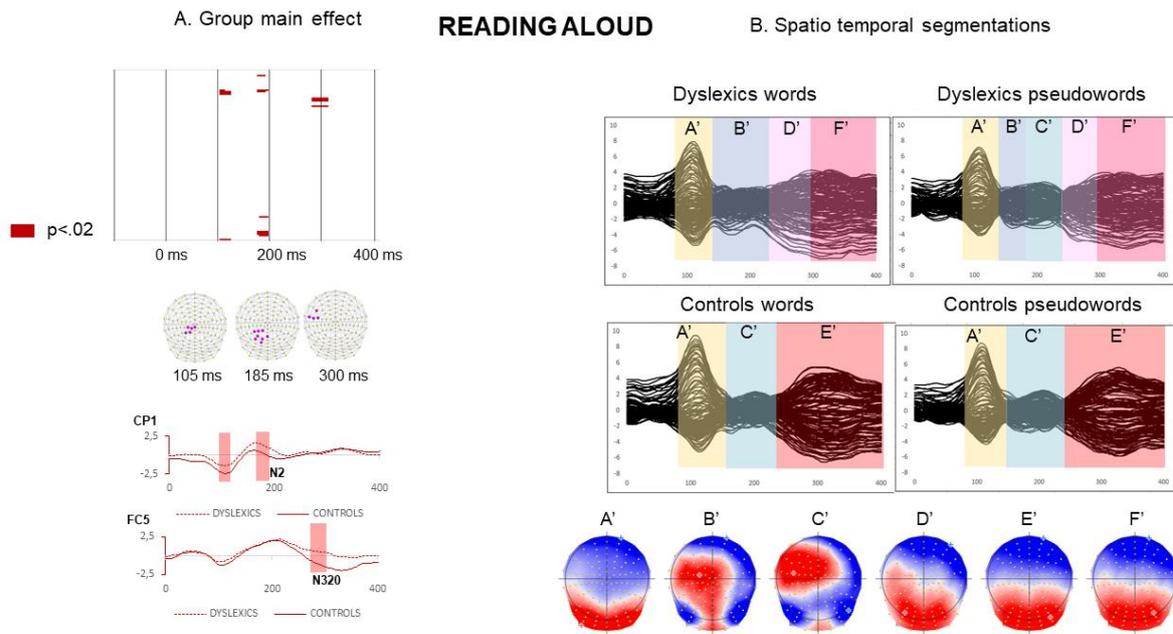
1 Figures



2

3 **Figure 1A.** Significant differences on ERP waveform amplitudes on each electrode (Y axes)
4 and time point (X axes) between dyslexic and expert readers for words and pseudowords and
5 interaction between stimulus type and group. Differences over at least four clustered
6 electrodes and 5 consecutive time frames (10 ms), with an alpha criterion of .02 are displayed
7 in red. The electrode sites yielding significant differences between the two groups at 240-250
8 ms and examples of waveforms (Pz) are displayed below **Figure 1B.** Grand average ERPs
9 (128 electrodes) for each group (dyslexics on the top and controls on the bottom) and each
10 stimulus type (words on the left and pseudowords on the right) and temporal distribution of
11 the topographic maps revealed by the spatio-temporal segmentation analysis. Colors illustrate
12 the time-window of each period of topographic stability. Corresponding map templates are
13 displayed below.

14



1

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

12

13

14

15

1 **Appendix**

2

3 **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}

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

5

6 **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}

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

8

9