How visual attention span and phonological skills contribute to N170 print tuning: an EEG study in French dyslexic students

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Abstract

Developmental dyslexia is a disorder characterized by a sustainable learning deficit in reading. Based on ERP-driven approaches focusing on the *visual word form area*, electrophysiological studies have pointed a lack of visual expertise for written word recognition in dyslexic readers by contrasting the left-lateralized N170 amplitudes elicited by alphabetic versus non-alphabetic stimuli. Here, we investigated in 22 dyslexic participants and 22 age-matched control subjects how two behavioural abilities potentially affected in dyslexic readers (phonological and visual attention skills) contributed to the N170 expertise during a word detection task. Consistent with literature, dyslexic participants exhibited poorer performance in these both abilities as compared to healthy subjects. At the brain level, we observed (1) an unexpected preservation of the N170 expertise in the dyslexic group suggesting a possible compensatory mechanism and (2) a modulation of this expertise only by phonological skills, providing evidence for the phonological mapping deficit hypothesis.

Keywords

1. Introduction

Becoming an expert reader requires a long learning process to efficiently integrate the visual form of words with the sounds of language. This explicit learning is underpinned by a progressive specialization of a left-lateralized network making the automatization of reading possible. Commonly admitted brain regions in this circuitry encompass: (1) the left fusiform gyrus including the visual word form area (VWFA; BA 37) which is typically associated with the visual recognition of the word (Cohen et al., 2000; Dehaene & Cohen, 2011); (2) the temporo-parietal areas (BA 39/40) involved in speech sound analysis and letter-to-sound conversion (Breier et al., 2003; Pugh et al., 2001); (3) the left inferior frontal gyrus (BA 44/45/47) reported as the unification space of semantic, syntactic and phonological operations into a representational structure spanning multiword utterance (Binder et al., 2009; Hagoort, 2005; Heim et al., 2009). Additionally, emerging evidence tends to support a bilateral contribution of the superior parietal lobule (SPL; BA 5/7) in the deployment of visual attention on the to-be-read word (Henry et al., 2005; Mayall et al., 2001; Rosazza et al., 2009; Valdois et al., 2019; Vialatte et al., 2021). Although structurally well established, dynamics of this network are still hotly investigated, notably to facilitate diagnose and clinical care for people with reading disabilities. In that respect, developmental dyslexia constitutes a well-suited model to explore underlying mechanisms of reading because of the wide spectrum of clinical deficits at the core of this trouble.

Affecting 3 to 10% of the population, developmental dyslexia is a public health problem interfering at an early age with school performance. This severe disorder is characterized by a specific and sustainable learning deficit in reading despite of normal intelligence, visual acuity and appropriate socio-educative environment (World Health Organization, 2011). It is now widely accepted that poor reading skills emerge from a cognitive disorder, itself secondary to a neurobiological dysfunction (see Ramus et al., 2018 for a review). Despite this consensus, different manifestations of dyslexia have been described and frequent co-occurrence of additional visual, motor, auditive or attentional symptoms has given rise to a major debate with respect to the nature of this disorder (Ramus et al., 2003; Reid et al., 2007; Valdois et al., 2004). Up to now, two very independent aetiologies have been reported: a specific deficit in phonological processing (Ramus & Szenkovits, 2008) or a limited ability to spread the visual attention (VA) window over a whole word (Bosse et al., 2007).

1.1. Phonological deficit hypothesis

The assumption of a phonological deficit at the core of developmental dyslexia is the most prevalent explanation to account for reading impairment (Ramus et al., 2003). Phonological deficit hypothesis postulates a weak development of phonological representations in terms of poorer quality (i.e. noisier, fuzzier or underspecified) (Harm & Seidenberg, 1999) or to an impeded access to these representations

(Boets et al., 2013; Ramus & Szenkovits, 2008). In turn, these difficulties would hamper the acquisition of phonological mapping (i.e. grapho-phonological correspondences) and therefore proficiency in reading.

1.1.1. Behavioural evidence

A large body of findings has described difficulties in dyslexic readers to perform cognitive tasks relying on phonological processing (Saksida et al., 2016; see Vellutino et al., 2004 for a review). Most of them include word and pseudoword reading tasks reflecting the ability to use decoding procedure to generate a word (Gough & Tunmer, 1986), phonological awareness tasks testing the ability to access and manipulate sublexical units of a word (Bentin, 1992) and phonological short-term memory tasks assessing the temporary storage of phonological information during decoding procedure (Jacquemot & Scott, 2006). Already present at a pre-reading stage in child who will become dyslexic (Law et al., 2017), these difficulties are thought as a major factor to account for the emergence of developmental dyslexia.

1.1.2. Neuroanatomical evidence

A strong corroboration of the phonological mapping hypothesis has come from investigations via fMRI due to its excellent spatial resolution. One of the main biological feature in the dyslexic population highlighted by this technique holds to a congenital disruption of the left perisylvian areas (Démonet et al., 2004; Richlan et al., 2011). The assumption of a degradation of phonological representations is congruent with atypical activities reported in the left inferior frontal gyrus (Cao et al., 2006; Paulesu et al., 2014; Peyrin et al., 2012) and in the left temporo-parietal areas (Rumsey et al., 1992; Temple et al., 2003) whereas dysconnectivity between these two regions is in line with the hypothesis of a hindered access to these representations (Boets et al., 2013; Vandermosten et al., 2012)

1.1.3. Consequence on visuo-orthographic processing

Beyond these areas dedicated to phonological processing, dyslexic readers are marked by a strong underactivation of the left occipito-temporal (OT) region which persists during the adulthood at the location of the VWFA (Paulesu et al., 2001; Richlan et al., 2011). According to McCandliss & Noble (2003), this impairment could be conceived as a consecutive effect following the primary dysfunction of the phonological-based regions. Poor decoding skills impede the acquisition of appropriate pronunciations associated with the visual form of word (or parts of the word) and therefore, the detection of regularities within the writing system. The gradual specialization of the VWFA response cannot therefore be established, leading to a disruption of the automatic response to word.

1.2. Visual attention span deficit hypothesis

Aside from phonological skills, VA abilities are particularly solicited in apprentice readers and constitute, with phonological abilities, the two best predictive factors -independently of one another- of reading and writing skills even before their formal learning (Bosse & Valdois, 2009; Plaza & Cohen, 2007). Specifically, visual attention could be solicited in apprentice readers in an analytic way (i.e. by a sequential process on each elementary unit of unfamiliar or new words encountered) allowing the development of orthographic knowledge (Ans et al., 1998). Thanks to the growing expertise in reading, the visual attention window could be deployed on the whole word, driving a global process for the fast and automatic visuo-orthographic recognition of the word. The core of the VA span deficit hypothesis in dyslexic population would be a reduction of the amount of visual information's processed simultaneously in a word, hampering both the sequential shifting of the VA window and the rapid and automatic visual recognition of the written words.

1.2.1. Behavioural evidence

Global and partial report tasks are commonly used to assess VA span, defined as the number of distinct visual elements processed simultaneously in a multi-elements string (Bosse et al., 2007). These tasks consist of orally reporting either all the letters (global report) or a specific letter (partial report) among a sequence of a consonant string briefly presented on a screen. As expected, a significant part of dyslexic readers is characterized by a reduction of the VA span comparatively to healthy subjects (Lobier et al., 2014; Reilhac et al., 2013). Moreover, a double dissociation between phonological and visual attention impairment has been reported in studies carried out both on clinical cases (dyslexic adults: Peyrin et al., 2012; dyslexic children: Valdois et al., 2003) and to larger samples of dyslexic children in different languages (Bosse et al., 2007), suggesting an independence between these two deficits.

1.2.2. Neuroanatomical evidence

A set of neuroimaging studies converges toward the involvement of the SPL in visual multi-elements processing (Mitchell & Cusack, 2008; Reilhac et al., 2013) but regardless of the nature of the stimuli, alphanumeric or not (Lobier et al., 2012). In expert readers, fMRI activation of the left SPL has been specifically associated with length effects in pseudo-words reading (Valdois et al., 2006) and is negatively correlated with proficiency in reading (Jobard et al., 2011). In that sense, developing children show stronger bilateral posterior parietal activity than proficient readers during reading activity (Church et al., 2008). In adulthood, the involvement of the posterior parietal cortex is therefore confined to the rare situations in which the automatic visuo-orthographic process is disrupted, inducing a sequential analysis on the word. Such is the case, for instance, of words displayed in mixed-case format (PET: Mayall et al., 2001) or rotated to some degrees and displaced to the visual periphery

(fMRI: Cohen et al., 2008). Importantly, in dyslexic readers suffering from a specific reduction of the VA span, a consistent underactivation of the SPL has been reported both in children (Peyrin et al., 2011) and adults (Lobier et al., 2014; Reilhac et al., 2013) comparatively to healthy subjects. Finally, the cognitively-based dissociation between phonological and VA span deficit has been substantiated biologically in two representative dyslexics (Peyrin et al., 2012). While an underactivation of the parietal lobules was only found in the dyslexic participant with a VA span reduction during a visual categorization task, a specific underactivation of the left inferior frontal gyrus was highlighted only in dyslexic with phonological impairment during a phonological rhyme task.

1.2.3. Consequence on visuo-orthographic processing

In this context, the persisting left OT disruption in dyslexic readers would result from an initial abnormality in the posterior parietal region. Supporting this hypothesis, a strong neurophysiological relationship between the VWFA and the dorsal attention network has been highlighted, especially during the first years of reading instruction (typical children: Moulton et al., 2019 ; dyslexic children : van der Mark et al., 2011). Given this connectivity increases with reading skills and age while such dynamics is not observed between the VWFA and the traditional reading-related regions (Vogel et al., 2012; but see Chen et al., 2019), these data suggest a visual attention component in the emergence of the automatic visuo-orthographic recognition of words.

To summarize, a strong set of behavioural and fMRI data has substantiated the two above-mentioned theoretical frameworks of developmental dyslexia; these two aetiologies being thought independent from each other. One main common characteristic, however, is a persisting disruption of the automatic visuo-orthographic recognition of the written word within the VWFA which could be subtended either by a primary deficit in phonological skills or by a poorer visual attention ability.

1.3. Event-related potential (ERP) approach as a tool to assess the VWFA integrity in dyslexia

While fMRI has been particularly useful to identify the location of the altered structures within the reading network in dyslexic readers, EEG technique offers the advantage to assess the temporal dynamics of the written words' recognition processing despite a lack of spatial accuracy. The neural specialization of VWFA in visual expertise for print is often assessed using ERP-driven approaches focusing on a well-known component: the N170. This component is characterized by a negative voltage variation emerging around 170 msec after visual stimulus presentation along the OT region. Within the left hemisphere, its sensitivity has been linked to visual properties of stimuli with a greater negative amplitude for letter strings than closely visually matched symbol or alphanumeric strings; this difference reflects the expertise to efficiently recognize written word stimuli (Araújo et al., 2012; Bentin et al., 1999; Maurer et al., 2005; Maurer et al., 2008). Importantly, although the ventral location

of the VWFA in the OT region leads to difficulties to pick up signals, studies combining both fMRI and EEG techniques have been able to report a correlation between the word-induced N170 amplitude and the activation pattern of the VWFA during reading (Brem et al., 2006). Furthermore, a convincing evidence has stemmed from intracranial recordings reporting a strong N170-like response at the vicinity of VWFA (Nobre et al., 1994), attesting the left-lateralized N170 ERP as a faithful marker of visuo-orthographic processing. However, in the context of dyslexia, a lack of this perceptual expertise has been largely reported in both child (Araújo et al., 2012; Maurer et al., 2007) and adult (Helenius et al., 1999; Mahé et al., 2012) populations. Not ascribed to a poor reading level (Mahé et al., 2013), this atypical pattern seems to be specific to clinical populations suffering from a VWFA dysfunction, that is, dyslexic or pure alexic readers (Mares et al., 2015).

1.3.1. N170 and phonological skills

Within the framework of McCandliss & Noble (2003), the N170-expertise for written words is explained by the constant and repeated use of grapheme-to-phoneme conversion over the course of reading acquisition ('phonological mapping hypothesis'). As the perceptual expertise emerges progressively during the two first years of reading, it corroborates the phonological mapping hypothesis (Maurer et al., 2005). The typical left-lateralized pattern of the N170-expertise for print is therefore conceived as the logical consequence of the strong engagement of the left hemisphere in phonological processes, as evidenced by a reduced lateralization of the N170 deflection in logographic scripts (Kim et al., 2004). According to the phonological mapping hypothesis, phonological ability, but not other measures of reading should predict the modulation of the N170 elicited in response to words. To our knowledge, three studies have investigated and corroborated this hypothesis: (1) typical children with higher phonological awareness performance demonstrate larger N170 lateralization for written word as compared to those with a poorer phonological skill score (Sacchi & Lazlo, 2016), (2) a lack of the N170 expertise for written words has been shown in adult dyslexic readers characterized by a phonological deficit (Mahé et al., 2012) and (3) the benefit of a letter-speech sound mapping training in dyslexic readers is reflected in the modulation of this N170 expertise (González et al., 2016).

1.3.2. N170 and visual attention component

Alternatively, a few electrophysiological studies attribute N170 expertise to visual attention ability. This is linked to the discussed role of the VWFA acting as a general visual processor representing each visual stimulus in variously sized chunks rather than specifically written letters or words (Vogel et al., 2014). In that sense, switching attention between different sets of elements as well as the size of attention spotlight have been reported as two factors modulating N170 response (Torriente et al., 1999). More specifically on written language, two reports in healthy population tend to support the

contribution of visual attention on N170 expertise. The first finding reports an early and efficient involvement of visual attention on appropriate part of letter strings is a necessary pre-requisite to drive a strong left-lateralization of the N170-response to words (Okumura et al., 2014, 2015; Uno et al., 2017; see also Yoncheva et al., 2010 in artificial scripts). The second finding is that manipulating orientation of the word presentation (standard vs inverted) results in different N170-responses. Specifically, rotated words elicit a larger N170 amplitude than standard words, presumably reflecting the switch between a holistic to a more local processing because of stimuli unfamiliarity (Proverbio et al., 2007).

Hence, from the EEG literature, it seems that the deployment of attention to appropriate parts of the written word may be a necessary but not a sufficient condition to drive the N170 expertise for words while phonological decoding could strongly influence its characteristic left lateralization. The goal of this study was to determine to what extent these two phonological and VA abilities contribute to the N170 expertise for written words in a sample of university dyslexic students and an age-matched control group. Experiment was conducted in three steps: (1) assessing behaviourally in each group the two above-mentioned cognitive abilities, (2) recording the N170 component amplitude while participants performed a word detection task (contrasting words and symbols string stimuli) and (3) testing the relationship between the behavioural variables and the N170 expertise for print.

2. Method

2.1 Participants

Twenty-two French native speakers diagnosed with developmental dyslexia (16 women and 6 men, mean age: 22.18 ± 3.5 years) and 22 adult controls (17 women and 5 men, mean age: 22.09 ± 3.15 years) matched on gender except one pair, duration of college studies (± 1 year) and age (± 2 years) took part in this experiment. All participants were students and reported normal or corrected-to-normal vision. Each dyslexic participant had completed several years of remediation training with a speech therapist (mean: 6,59 ± 3.12 years). Participants who had any history of neurological illness or brain damage and sustained general anesthesia or used benzodiazepines or substance abuse during the three months prior to testing were excluded. Non-verbal intelligence was assessed by Raven's Progressive Matrices (Raven & Raven, 2003) to verify the absence of global delay. Characteristics of each group are summarized in *Table 1*.

The protocol was approved by the local Ethics committee and conducted in accordance with the ethical standards prescribed in the 1964 Helsinki Declaration and subsequent amendments to the declaration. All participants gave their written informed consent.

	Dyslexics (n=22) Mean (SD)	Controls (n=22) Mean (SD)	*t*-test
Gender (female : male)	(16:6)	(17:5)	
Age (years)	22.18 (3.5)	22.09 (3.15)	t(42) = 0.09 ; p = .93
Raven's Progressive Matrice (score)	49.36 (5.09)	51.18 (5.13)	t(42) = -1.18 ; p = .24

Table 1 : Characteristics of participants

2.2 Behavioural assessment

Prior to the experiment, a behavioural assessment including four reading, two visual-attentional and two metaphonological tasks was performed in all participants.

2.2.1 Reading tasks

2.2.1.1 Alouette test

Oral reading skills were assessed using "L'Alouette", one of the most widely used reading test by health professionals in Francophone-speaking countries to screen dyslexia among children and adults (Lefavrais, 2005; Cavalli et al., 2018). This test consists of a text of 265 real words constructed with grammatically and syntactically correct but meaningless sentences. It taps on lexical and sublexical procedure by the presence of grapheme-phoneme correspondences and irregular words. In addition, the use of contextual expectations as a compensation strategy (Rack et al., 1992) is prevented by the presence of words that are similar to those suggested by the context (e.g., poison [poison] instead of poisson [fish] after lac [lake]). Each participant had to read aloud as rapidly and accurately as possible this text with a 3 min time limit. Fluency was measured with a normative score (CTL) based on reading time and the number of correctly pronounced words.

2.2.1.2 LEXTALE_FR test

In addition to "L'Alouette", silent reading skills were evaluated with the LEXTALE_FR adult test (Brysbaert, 2013). A random list of 56 French words of varying difficulty and 28 French-looking non-words was presented to the participants. They were required to report only words among this list. The recorded measurement was a Ghent-score based on number of errors and correct responses.

2.2.1.3 Pseudoword reading (PW)

In order to specifically assess the sublexical procedure in reading, we used a pseudoword reading task of EVALEC software, a computerized battery of tests of reading and reading-related skills (Sprenger-Charolles et al., 2005). The task consisted of 36 pseudowords that participants had to read as quickly

and accurately as possible. The recorded scores were the percentage of correct answers and the naming latencies in milliseconds.

2.2.1.4 Irregular words reading (IRR)

Finally, the lexical procedure in reading was assessed with a task of irregular word reading (EVALEC; Sprenger-Charolles et al., 2005). All the participants had to read as quickly and precisely as possible a list of 20 irregular words: 10 short and 10 long. The 20 words were presented under the same conditions as the pseudowords. The recorded scores were the percentage of correct answers and the naming latencies.

2.2.2 Metaphonological tasks

2.2.2.1 Phonological awareness (AWA)

Phonological awareness was assessed by a phonemic deletion task (EVALEC; Sprenger-Charolles et al., 2005). Participants heard one by one 12 peudowords with a consonant-consonant-vowel structure (e.g. /spo/) through headphones and had to repeat each item without the first phoneme as accurately as possible (/po/). The recorded score was the percentage of correct answers.

2.2.2.2 Phonological short-term memory (STM)

This task (EVALEC; Sprenger-Charolles et al., 2005) involved repetition of 24 pseudowords from three to six syllables (i.e. 6 items per syllabic length). Participants heard the items one by one through headphones and had to repeat each of them. Items were presented in such a way that syllable length increased progressively during the task. Behavioural measurement was defined as the series for which the participant gave at least 4 correct responses out of 6.

2.2.3 Visual-attentional span tasks

To assess visual attentional component, two tasks of the EVADYS software (Valdois, 2017) were used.

2.2.3.1 Global Letter Report (GLO)

Participants were asked to orally report a string of 6 letters briefly presented on the monitor screen. At the start of each trial, a fixation point appeared during 1000 ms at the center of the display followed by a blank screen for 500 ms. Then, an unpronounceable string of six letters (e.g., R H S D M K) was presented. Participants had to verbally report all the letters immediately after they disappeared. The experimental task was preceded by four training trials for which participants received feedback. No feedback was given during the 20 test trials. The score was the percentage of letters accurately reported across all the trials.

2.2.3.2 Partial Letter Report (PAR)

The participants were required to orally report a single cued letter among the 6 letters of each briefly presented string. Experimental task included the same steps than the previous one but at the offset of the letter string presentation, a vertical bar cue appeared for 50 ms below one letter. Participants were asked to orally report the cued letter only. The experimental task was preceded by twelve training trials with feedback. No feedback was given during the 60 test trials. The score was the percentage of letters accurately reported across all the trials.

2.3 Electrophysiological experiment

2.3.1 Word detection task

Participants performed a word detection task during the EEG recording. Each trial began with the presentation of a fixation cross at the center of a black screen during 500 ms (eye-cross distance: 57 cm). A black screen replaced the fixation cross during 120 ms and then, the stimulus which was a word or a symbols string appeared during 500 ms (visual angle ~3°). This was followed by a black screen for 1500 ms and participants were asked to decide as quickly and accurately as possible whether the stimulus was a real word or not by pressing a "YES" response key or a "NO" response key. A total of 210 stimuli were used for the experiment. Half of these were five-letters monosyllabic words selected from the French database *Lexique 3* (New et al., 2001) with a high lexical frequency (mean : 190,7 words per million ; range 46,1 - 732,4) and the other half were five-symbols strings (e.g. : Ø *‡¬¥). The battery of the symbols stimuli chosen for this task was similar to those used and illustrated in Mahé et al. (2012). Stimuli were presented on a monitor screen (white print, black background) and written in "Courrier New" font within 28 points lowercase letters. Recorded scores were response time (RT) and percentage of correct answers.

2.3.2 EEG recording

The EEG was recorded continuously via 64 channels distributed according to the 10-20 system. Recording was sampled at a rate of 512 Hz and filtered online between 0.01 and 500 Hz. Extraction and processing of the EEG signal were performed offline thanks to Brain Vision Analyzer software. Data were re-referenced to the average reference and a notch filter was applied at 50 Hz. ERP segments of correct answers were epoched from -200 before to 800 ms after the stimulus onset. A baseline correction was applied over a 200 ms interval preceding the presentation of the stimulus. Trials with voltages exceeding +/- 100 µV were defined as artifacts and excluded from further analyses. Overall, we excluded 6.37% of the trials in the control group and 9.84% in the dyslexic group. N170 was automatically defined as the more negative peak between 150 and 200 ms. In accordance with the study conducted by Mahé et al. (2012) and the visual inspection of individual ERPs, a time window between 135 and 255 msec was defined for the N170 mean amplitude analysis.

2.4 Data analysis

2.4.1 Behavioural analysis

First, independent-samples *t*-tests were used to compare performances of the dyslexic and the control group in each task. As largely reported in previous studies (e.g., Bosse et al., 2007; Saksida et al., 2016), we predicted significant worse performances in the dyslexic group in each task. Second, we performed a principal components analysis (PCA) on all behavioural performances to reduce the number of variables to factors underlying independent phonological and visuo-attentional skills. Such an analysis has already proven to be useful and effective to identify both phonological and visuo-attentional factors in previous studies (Bosse et al., 2007; Zoubrinetzky et al., 2014). Based on them, we expected to find these two independent factors. Finally, the variables with high weighting on the phonological factor and low weighting on the visuo-attentional factor, and vice versa, were entered as predictor variables of the N170 print tuning in a multiple regression analysis.

2.4.2 EEG analysis

The N170 event related potential has been extracted for each participant at the P7 (left OT area) and P8 (right) electrodes. Analyses were carried on the mean latency and the mean amplitude of the component. Repeated measures ANOVA were conducted with group (controls, dyslexics) as between-subject factor and stimulus type (word or symbol strings) as well as hemisphere (left: P7 channel; right: P8 channel) as within-subject factors. We expected a significant Stimulus * Hemisphere * Group interaction with a greater amplitude for words than for symbols in the left hemisphere in the control group but not in the dyslexic group. Moreover, we analyzed whether the N170 expertise was more predicted by phonological or visuo-attentional skills. Multiple regression analysis was performed separately in each group. The index of the N170 expertise was computed by the following formula:

$$N170_{expertise} = (N170_{Word} - N170_{Symbol})_{Left} - (N170_{Word} - N170_{Symbol})_{Right}$$

in which each term represents the N170 amplitude for the *Word* or *Symbol* condition separately for the *Left* and the *Right* hemisphere. Based on previous studies (e.g., Mahé et al., 2013), we predicted at least an association between phonological skills and N170 expertise and potentially an association between VA skills and N170 expertise. As an additional information, we finally conducted full-factorial analyses of covariance (ANCOVA), including Group, Hemisphere and Stimulus factors and the two behavioural variables identified via the PCA as continuous predictors. The results of the ANCOVA should be taken with cautious as the restricted number of participants. We expected a significant Group*Hemisphere*Stimulus*phonological variable interaction.

3. Results

3.1. Behavioral data

3.1.1 Overview of the participants' performance

Behavioural performances of the dyslexic and control groups are presented in *Table 2*. Significantly differences were reported in all reading, visual attentional and metaphonological tasks with best performances in favour of healthy participants.

	Dyslexics (n=22) Mean (SD)	Controls (n=22) Mean (SD)	*t*-test
Reading tasks			
Alouette (*CTL*)	313.04 (64.42)	507.49 (93.08)	t(42)= - 8.06 ***
LEXTALE_FR (*Ghent-score*)	59.67 (15.42)	81.61 (9.37)	t(42)= - 5.7 ***
PW (*% correct answers*)	69.09 (20.44)	95.45 (4.81)	t(42)= 5.89 ***
PW (*latency*)	1 209.55 (472.58)	709.05 (107.18)	t(42)= 4.84 ***
IRR (*% correct answers*)	90.45 (12.99)	98.64 (2.28)	t(42)= 2.91 **
IRR (*latency*)	971.23 (394.35)	647.25 (62.54)	t(42)= 3.81 ***
Metaphonological tasks			
AWA (*% correct answers*)	80.30 (16.38)	94.7 (6.06)	t(42)= 3.87 ***
STM (*span*)	4.5 (1.44)	5.23 (.75)	t(42)= - 2.1 *
Visual-attentional span tasks			
GLO (*% correct letters*)	68.37 (13.12)	78.3 (9.62)	t(42)= - 2.86 **
PAR (*% correct letters*)	79.47 (12.08)	85.83 (6.84)	t(42)= - 2.15 *

Table 2 : Results of the dyslexic and control groups in each reading task (PW : pseudowords reading task ; IRR : irregular words reading task), metaphonological tasks (AWA : phonological awareness task ; STM : phonological short term memory task) and visual attentional span tasks (GLO : global letter report ; PAR : partial letter report). (**: p <.01 ; *** : p <.001).

3.1.2 Principal component analysis

In order to identify phonological and visuo-attentional factors, we conducted an exploratory PCA across all the behavioural variables (*Table 3*). Rather than highlighting two factors, our data were better described through three factors accounting for 75.73% of the variance. The first factor (called

"Reading") accounted for the 50.63% of the variance and received high loadings from all reading speed and accuracy measures, the prominent account stemming from Alouette performances ($Ft1_{Alouette}$ = .86). The two other factors accounted for 14.31% and 10.79% of the variance and were consistent with our two cognitive functions of interest, that are phonological (Ft2) and VA (Ft3) abilities. Higher values of AWA and STM indicated a higher phonological factor score. Importantly, while both AWA and STM loaded similarly onto it (.64 and .68, respectively), the difference in factor loadings between factors of interest is larger for AWA (.64 and -.04 in the phonological and VA factors, respectively) than for STM (.68 and -.44 in the phonological and VA factors, respectively). These results suggested that AWA was the variable the most related with the unique phonological dimension. In the VA factor, higher values of GLO (.55) and PAR (.61) indicated a higher VA factor score. More importantly, PAR score constituted the most sensitive VA-related parameter as it loaded poorly to the phonological factor (.11 versus .39 for the GLO parameter). This set of results led us to reject the possibility of using the PCA composite factors for our further analyses as they do not reflect accurately the independence of Phonological and VA abilities. Rather than using composite PCA scores, we chose specific scores (AWA and PAR) that loaded heavily on one factor and very lightly on the other.

| | Factors (Ft) loadings | | |
	Ft1	Ft2	Ft3
	'Reading'	'Metaphonology'	'Visual Attention'
Alouette (*CTL*)	**.86**	.03	-.13
LEXTALE_FR (*G-score*)	**.80**	.13	-.21
PW (*% cor*)	**.84**	-.28	-.15
PW (*latency*)	**-.84**	.32	-.15
IRR (*% cor*)	**.72**	-.29	-.32
IRR (*latency*)	**-.83**	.35	-.05
AWA (*% cor*)	.52	**.64**	-.04
STM (*span*)	.39	**.68**	-.44
GLO (*% correct letters*)	.56	.39	**.55**
PAR (*% correct letters*)	.58	.11	**.61**

Table 3. Factors extracted from the principal components analysis through all the variables evaluated during the behavioural assessment. For the sake of clarity, bold values depict the highest load of each variable among the three identified factors (in other words, the most representative variables for each factor).

3.2. EEG experiment data

3.2.1 Behavioural data

Analysis of word detection task data was conducted on the mean correct reaction time (RTs) and percentage of errors. For RTs analysis, nor group effect ($F_{(1,42)}$ =1.81 ; p=.19) nor group x stimulus interaction F<1 was reported but a significant effect of stimulus has been revealed ($F_{(1,42)}$ = 13.78 ; p < .001) with shorter RTs for word stimuli (mean 460.8 ± 88.1 ms) than for symbol string stimuli (mean 474.78 ± 87.93 ms). For error rate analysis, only the group effect approached significance ($F_{(1,42)}$ = 3.29 ; p =.08) with a lower rate of errors in control (1.93 ± 1.63%) than in dyslexic participants (3.44 ± 3.96%). Nor group x stimulus interaction (F<1) nor stimulus effect (F<1) was reported.

3.2.2 N170 component analysis

EEG signal at the left (P7) and right (P8) OT channels for each group and stimulus type are presented in Figure 1. Related topographical maps of the electrical activity during the period of interest (135-255 ms) are depicted in Figure 2 for each group and each condition.
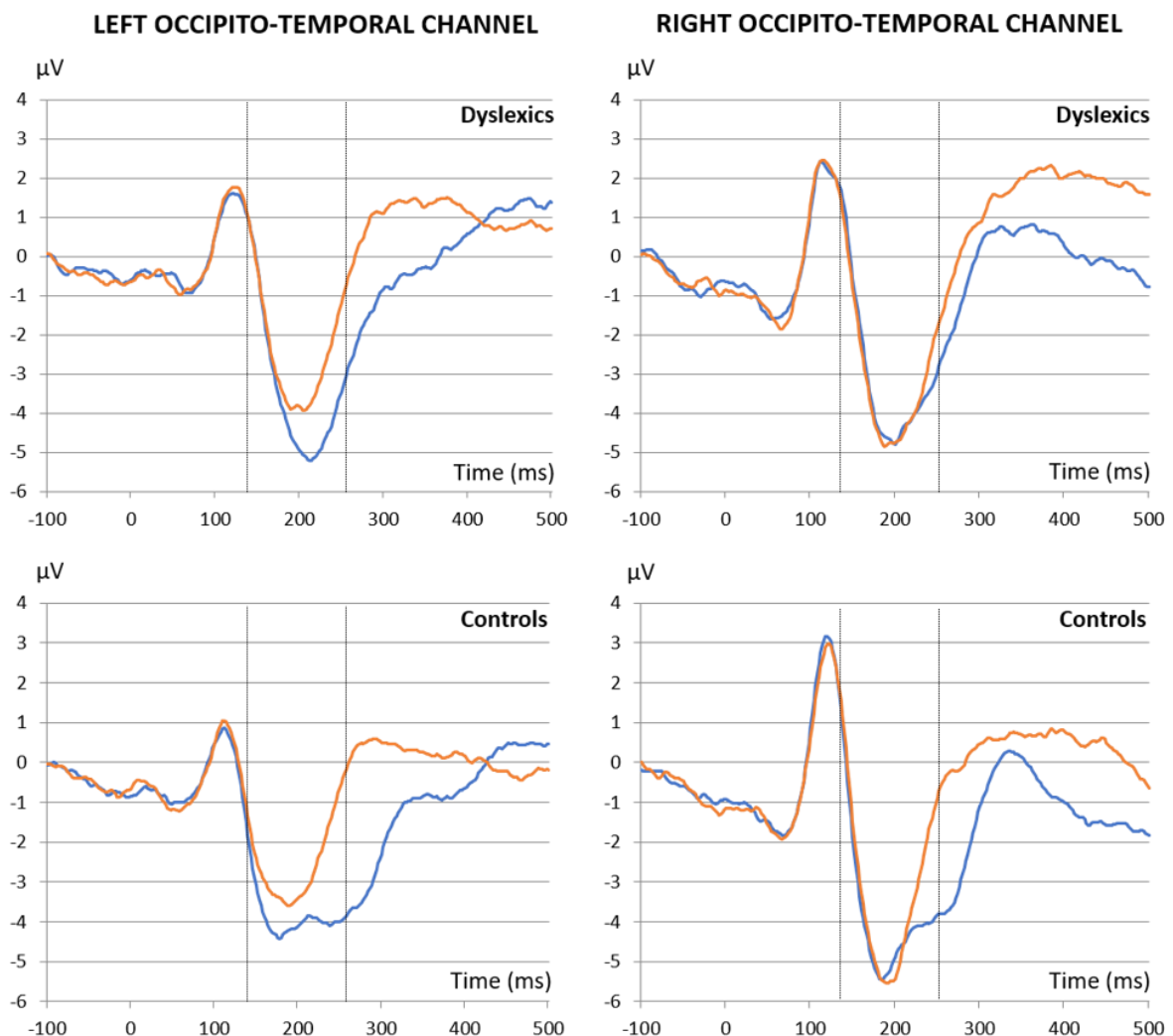
Figure 1. Waveforms at the P7 (left) and P8 (right) OT channels for each group (n=22) and stimulus type (blue: words; orange: symbol strings). N170 mean amplitude was measured in a latency range of 135–255 ms (dashed lines).

3.2.2.1 Latency

In terms of N170 latency, dyslexic and control group did not differ significantly (F<1) but a stimulus effect was reported ($F_{(1,42)} = 4.09$; $p < .01$) with shorter latencies for symbol strings (194.6 ± 5.57 ms) than for words (201 ± 7.83 ms).

3.2.2.2 Amplitude

Overall, N170 amplitude was significantly greater for words than symbol strings ($F_{(1,42)} = 32.57$; $p < .001$). This difference was more pronounced in the left than in the right hemisphere, as revealed by the expected Stimulus * Hemisphere interaction ($F_{(1,42)} = 13.16$; $p < .001$). The interaction between group and stimulus only approached significance ($F_{(1,42)} = 3.93$; $p = .06$) and, the Stimulus * Hemisphere * Group did not reach significance ($F_{(1,42)} = 0.91$; $p = .34$): , the difference between words and symbol strings in the left OT channel was significant for the control group ($F_{(1,42)} = 39.7$; $p < .001$) but also for the dyslexic sample ($F_{(1,42)} = 11.13$; $p < .001$).
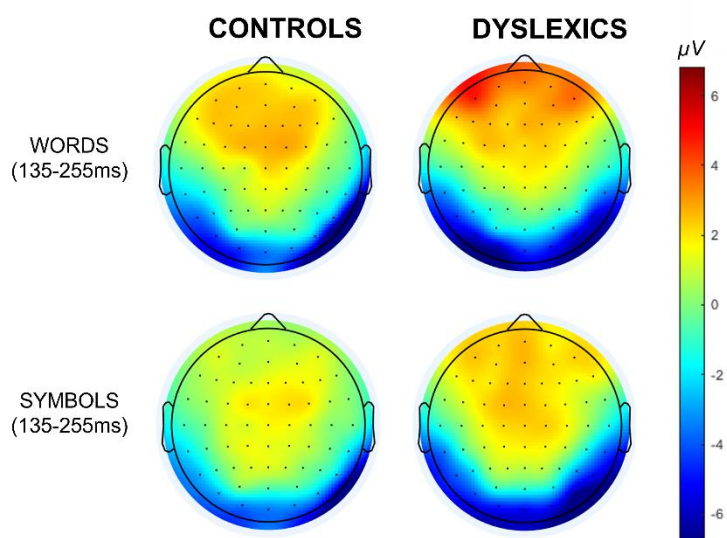

Figure 2. Topographical maps for each type of stimulus (top : words condition ; bottom : symbols condition) during the N170 period of interest (135–255 ms) for controls (left) and dyslexics (right).

3.2.2.3 Contribution of phonological and VA abilities to the N170 expertise

Two analyses aimed to explore the contribution of visuo-attentional and phonological skills derived from the PCA to the N170 expertise. In a first step, two multiple regressions analyses, separately for the dyslexic and the control group, were performed in which AWA and PAR scores were entered as predictors and the index of N170 expertise as the dependent variable. In the dyslexic group, only the AWA score (β = -.57, t = -2.81, p =.01) but not the PAR score (β = .27, t = 1.31, p =.20) significantly predicted the left lateralization of the N170 response: the higher participants' AWA scores, the greater the N170 left lateralization. In control group, however, no such effect was reported for any of the predictor variables (AWA : β = .09, t <1, NS ; PAR : β = .11, t <1, NS). As shown in Figure 3, the lack of association between AWA scores and the N170 index in control group could be due to a ceiling effect, which was not observed in the dyslexic group.
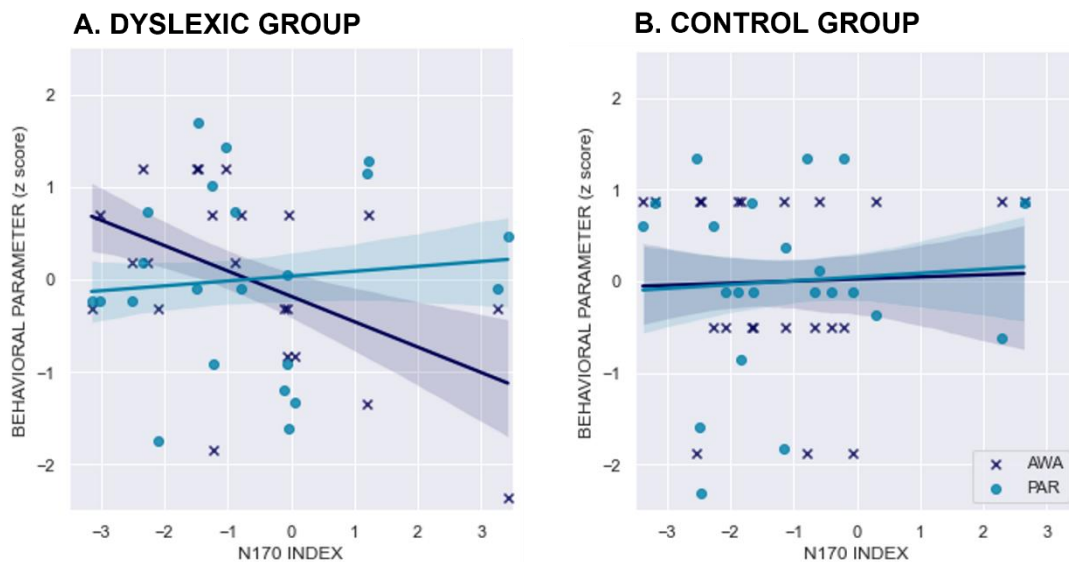

Figure 3. Association between index of N170 expertise and predicted AWA and PAR variables identified in the PCA analysis (for a better comparison between each variable and group, the behavioral measurements have been converted in z scores). Each marker represents the performance of a participant in the AWA (purple) and in the PAR tasks (blue). Note that performance of participants have been converted into z-scores, meaning that the preponderance of values toward 1 in the control group regarding the AWA ability reflects a ceiling effect (100% correct responses). For the clarity of the illustration, linear regression lines are shown with a CI defined at 75% (the analyses have been conducted with a CI at 95%). A: Associations obtained in the dyslexic group ; B: Associations obtained in the control group.

In a second step, we included AWA and PAR scores as continuous predictors in a full factorial analyse of covariance (ANCOVA) with Group, Hemisphere and Stimuli. While the Group*Hemisphere*Stimulus*AWA score interaction was significant ($F(1,38) = 5.71$; $p = .02$), no interaction between Group*Hemisphere*Stimulus*PAR was significant ($F(1,38) = .45$; $p = .51$).

4. Discussion

The goal of the present study was to determine the contribution of phonological and visual attention skills to the left OT N170 print tuning in a sample of dyslexic readers. Previous studies hypothesized that these two skills are crucial factors to the emergence of this specialization, the former by paying attention to appropriate parts of the to-be-read word, the latter by the repeated use of grapho-phonemic association during reading acquisition. Consistent with literature, the behavioural results showed that dyslexic readers do not reach performance of normoreaders in all reading, phonological and visual attention tasks. The PCA allowed us to identify specific and independent measures of phonological and VA skills, i.e., performances at the phonemic deletion task (AWA) and at the partial letter report task (PAR). At the brain level, we reported two interesting results: (1) an unexpected preservation of the left N170 specialization in the dyslexic sample and (2) a relationship between phonological skills -but not visual attention ability- and the modulation of left lateralized N170 expertise.

4.1. On the modulation of N170 expertise by phonological skills

Based on multiple regressions and full factorial analyses, our results point to a contribution of phonological -but not visual attention- abilities to the modulation of the left-lateralized N170 expertise for written word recognition. This result anchor to the recent study conducted by Chen et al., (2019) in which functional and structural connectivity of VWFA with language and attention networks were investigated in a large cohort of healthy subjects. They showed that structural connectivity joining VWFA with latero-temporal language network predicted only language ability while the structural connectivity targeting dorsal fronto-parietal attention network predicted visuo-spatial attention -but not language- skill. Interestingly, the association that we find between phonological awareness and N170 expertise was mainly driven by the performance of the dyslexic group but not healthy participants for which a ceiling effect emerged (see *Figure 3B*). This result echoes ERP studies attesting for a modulation of the N170-expertise after letter-speech sound mapping training in dyslexic readers (Gonzàlez et al. 2016) and closely parallels to the Mahé et al. (2013) study whose results showed a correlation between the left lateralized N170 expertise and phonological abilities. Hence, a difficulty in decoding ability affecting the gradual specialization of the VWFA seems to be the more reliable explanation to account for the electrophysiological behaviour observed in our dyslexic group

(*'phonological mapping hypothesis'*: McCandliss & Noble., 2003). Thereby, their additional behavioural deficit in visual-attention ability reported in *Table 2* could be considered as a secondary associated disorder (Saksida et al., 2016) which not impedes the left-lateralized N170 expertise. Note however that this does not mean that there is absolutely no influence of VA ability on visual word recognition but this influence could be restricted to specific conditions when a deeper analysis of the stimulus has to be done (Yoncheva et al., 2010).

4.2. On the unexpected preservation of the N170 expertise for words in dyslexic participants

A very surprising result of this study which could have a crucial importance in the interpretation of our data is a preservation of the left lateralized N170 specialization for print in our sample of dyslexic readers.

In the literature of ERP studies dedicated to the link between left-N170 component properties and visual word recognition, researchers found that this marker could be sensitive to a large range of language-specific processing (orthographic: Rossion et al., 2003; phonological: Sacchi & Laszlo, 2016 and semantic: Segalowitz & Zheng, 2009) and to other factors such as attentional load (Mohamed, 2018) or visual familiarity (Xue et al., 2019). Hence, the kind of the task used during the EEG-recording could have different effect on the print-specific N170 modulation (for instance, see Faísca et al., 2019 for a comparison of N170 sensitivity between explicit and implicit reading tasks). Importantly, the word detection task used in the present study: (1) was not performed over an extended time period, preventing any effect of sustained attention and (2) did not require a strong reliance on lexical access and/or orthographic rules since a sole automatic low-level visual processing (based on visual features) was sufficient to decipher alphabetic from symbol characters. This led us to assume that our electrophysiological results have captured the 'pure' effect of visuo-orthographic processing, consistent with previous studies using short and simple tasks requiring a low attentional load (e.g. oddball paradigm: Bentin et al. 1999 or repetition detection tasks: Brem et al. 2006). Consequently, the exciting preservation of the written word early processing in our dyslexic group could mean that the left OT reading network is functional when a basic analysis of a character string (alphabetic versus non-alphabetic) must be done.

Another possibility accounting for the preservation of the visual recognition of written words in the dyslexic group is the specific sample that we have recruited (university students). Recent findings point to a potential development of compensatory mechanisms and/or a reorganization of the reading-related neural circuitry in such dyslexic population (Cavalli, Colé, et al., 2017). Although speculative, this hypothesis seems plausible in our context because of the properties of the words that we used in our task (short and of high frequency). The frequent exposure to the visuo-orthographic form of high frequency words during schooling has been shown to facilitate the development of

vocabulary knowledge and potentially the word recognition process (Martin et al., 2010). In that sense, by comparing young dyslexics and their control group on the one hand and university dyslexics and their control group on the other, Miller-Shaul (2005) has reported a significantly smaller difference in orthographic skills between the two adult groups as compared to those observed in young participants. In dyslexic students, Cavalli et al. (2016) showed also that despite a deficit in phonological abilities, vocabulary skills were preserved in such population (as compared to chronological-age controls) in terms of number of known words and accuracy / precision of word knowledge.

Obviously, this proposal does not rule out the possibility that our dyslexic sample could exhibit an abnormal pattern in other electrophysiological components. Although beyond the scope of this paper, our results could corroborate this point of view considering two observations. First, a striking difference over the left hemisphere between the two groups during our period of interest (135-255 ms) is a double negative deflection following a written word presentation in the control group as compared to the dyslexic group (Figure 1). To our knowledge, this 'double' pattern has been observed several times (e.g., Mahe et al, 2012,2013 ; Curzietti et al., 2017, 2018) and interpreted by (Simon et al., 2004). Authors suggested that the first (N170) component could act as the first discriminative step dissociating between orthographic and non-orthographic stimuli while the second (N230) component could reflect a sensitivity not only to the orthographic properties of the stimuli, but also to their phonological and lexical dimensions (which could be disrupted in our dyslexic sample). Although this hypothesis is attractive considering the phonological behaviour of our dyslexic readers, it remains speculative since our task should not solicit a strong reliance on these two latter properties. Second, as shown in Figure 2, the topographical map of dyslexic readers during the word condition shows a stronger activity pattern at the level of the left frontal area as compared to those observed in the control group. This observation echoes the hypothesis of a spatiotemporal reorganization of the reading network in university dyslexic readers (Cavalli, Colé, et al., 2017). Specifically, a greater reliance on the semantic cues contained in morphemes could be use by students with developmental dyslexia to manage their reading disability (Cavalli et al., 2016; Cavalli, Colé, et al., 2017; Cavalli, Duncan, et al., 2017; Law et al., 2018; Martin et al., 2012). At the neurophysiological level, this mechanism has been shown to rely on an earlier solicitation of the frontal network associated with morphological and semantic properties of the words (Cavalli, Colé, et al., 2017). Taken together, we suggest that due to the properties of our word condition and more broadly to the relatively transparency of the French language (relying mostly on high frequency rather than irregular words), this 'compensation hypothesis' could constitute a good interpretation of the unexpected preserved left-lateralized N170-expertise for words in our dyslexic sample and of the associated atypical activity pattern.

Conclusion / Perspectives

Our study offers new perspectives regarding developmental dyslexia. In conjunction with previous ERP studies (Mahé et al., 2013; Gonzales et al., 2016), we showed that the print-specific N170 is strongly sensitive to phonological skills when an early, superficial analysis over the letter string is performed. These results consolidate the assumption that left-lateralized N170 is a sensitive hallmark to diagnose phonological-based developmental dyslexia and support the *phonological mapping hypothesis* (McCandliss & Noble, 2003), at least in university dyslexic students. However, we did not provide evidence of a contribution of visual-attentional skills on the N170 print processing. Developmental studies with dyslexic children could help to define the potential critical time periods where the N170 print-tuning is sensitive to visual attention ability and obviously, to phonological ability.

Acknowledgments

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