

Impaired neural discrimination of regular words from pseudowords in dyslexic adults as revealed by fast periodic visual stimulation

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ABSTRACT

We used Fast Periodic Visual Stimulation with EEG recordings to assess the sensitivity of adults with dyslexia to fine-grained psycholinguistic variations of letter strings: lexicality and orthographic regularity. Dyslexic and non-dyslexic university students watched 60-s streams of stimuli presented at 10 Hz with deviant items (words) inserted periodically (1/8, at 1.25 Hz). While there was no overall difference in neural response between groups at the base stimulation frequency (10 Hz), individuals with dyslexia showed significantly reduced 1.25 Hz discrimination response for regular and irregular words among pseudowords (lexicality) over the left occipito-temporal cortex. Interestingly, while dyslexic individuals had significant weaker responses for irregular words than normal readers, they did not show any discrimination response for regular words within streams of pseudowords. However, they displayed responses to regularity changes within streams of words, that were not significantly below typical readers'. Overall, these observations suggest that lexical processes are not automatically triggered in dyslexia when a decoding strategy is enhanced by context (i.e., pseudowords) but may be at work when the overall activation of the lexicon is high (i.e., words). The results also show the diagnostic value of the FPVS-EEG approach to determine and characterize reading impairments rapidly, objectively and implicitly.

1. Introduction

Reading is a common activity at the interface of vision, language, and semantics that seems spontaneous and effortless for most of human adults in literate societies. Yet, between 5 and 10 % of individuals never acquire a fast, flawless, and automatic reading ability, and have difficulties even for recognizing single words (in French: [INSERM, 2007](#)). These dyslexic adults struggle with reading throughout their life ([Callens and Brysbaert, 2019](#); [Reis et al., 2020](#)), even if they developed compensation strategies to read complex sentences and texts.

The main objective of the present study is to provide evidence for atypical word-selective neural responses in such high-performing dyslexic individual adults (higher education students, mostly attending university) with a simple, sensitive, and objective approach: Fast Periodic Visual Stimulation (FPVS, or frequency-tagging) with electroencephalogram (EEG) recordings. Specifically, different letter

strings are presented at a fast periodic rate (i.e., 10 per second, 10 Hz, frequency f) during short periods of time (i.e., 60 s sequences), leading to an objectively identified 10 Hz response in the recorded EEG of the participants. By inserting a deviant category of stimuli (e.g., words) periodically (e.g., every 5 items) within the stream of base stimuli (e.g., nonwords), a word-selective neural response is objectively identified and quantified at $f/5$ and harmonics ($2f/5$, $3f/5$, ...) in the EEG spectrum ([Lochy et al., 2015, 2018, 2024](#)). This response reflects an index of differential processing between deviant (e.g., words) and base categories (e.g., nonwords). In the initial demonstration of this effect 10 years ago, such word-selective responses were found (mainly over the left occipito-temporal cortex) in neurotypical adults by presenting words as deviants within streams of pseudo-letters, of non-words, or even pseudowords ([Lochy et al., 2015](#)). The amplitude of the word-selective response was modulated by the contrast between words and base stimuli, being stronger within pseudofonts (coarse contrast)

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than within nonwords (pre-lexical contrast) and pseudowords (lexical contrast), respectively (Lochy et al., 2015). In 5 years old pre-readers, no response was found for words among pseudowords (i.e., no lexical discrimination), but letter-strings were discriminated against pseudowords, with amplitudes directly related to children letter's knowledge (Lochy et al., 2016). The same FPVS-EEG approach has also been used to track developmental changes over the first year of schooling (van de Walle de Ghelcke et al., 2021), to compare teaching methods (van de Walle de Ghelcke et al., 2020) or reading ability (Lutz et al., 2024), to evidence the emerging sensitivity to morphemic structure in young children (Pescuma et al., 2022), or (with a slightly different paradigm), to assess lexical responses in young children (Wang et al., 2022, 2023). However, to our knowledge, the approach has not yet been used to assess automatic visual word discrimination in adults with dyslexia (DYS), which is the objective of the present study.

Specifically, here our aims were to investigate 1) whether *DYS* have reduced lexical responses for words presented within pseudowords (word-selective responses, i.e., automatic lexical access); 2) whether lexical access is modulated by word regularity in a deep orthography like French; and 3) whether words are automatically distinguished according to regularity and lexical frequency. Based on models of (impaired) visual word recognition and previous literature, we derived several hypotheses.

First, when comparing individuals with dyslexia (*DYS*) to typical readers (*TR*) on automatic words-pseudowords (*W* vs. *PW*) discrimination (Fig. 1), we expected reduced voltage amplitudes in the selective (i.e., differential) activity elicited by words among pseudowords. Indeed, several meta-analyses of brain-imaging studies investigating functional neural mechanisms in *DYS* during reading tasks have found consistent hypoactivity in the whole reading brain network (Cattinelli et al., 2013; Maisog et al., 2008; Martin et al., 2016; Paz-Alonso et al., 2018; Pollack et al., 2015; Richlan, 2012; Richlan et al., 2009) and, especially, impaired automaticity in visual word recognition (Van der Mark et al., 2009). Similarly, EEG studies have revealed impaired tuning to print, impaired and slow grapheme-phoneme conversion processes, impaired sublexical orthographic analysis and lexical access, as well as impaired phonological access as revealed in relatively late Event-Related Potentials (ERPs) in dyslexia (Araújo et al., 2012, 2015; Dujardin et al., 2011; Mahé et al., 2012, 2018; Shaul, 2012; Silva et al., 2022; Taroyan and Nicolson, 2009). Given the lower reading performance of *DYS* and the recent report of a relationship between reading efficiency and response amplitudes for word-selective lexical responses (Marchive et al., 2025), we also hypothesized to find a positive correlation between reading abilities and response amplitudes.

Second, we expected this difference between groups to be modulated by word regularity. In regular words, pronunciation corresponds to the grapheme-to-phoneme conversion (GPC) rules while irregular words violate that/those rule(s) (Fig. 1). A related but different distinction in the literature considers that word pronunciation should be viewed on a continuum of word consistency¹ rather than on a binary distinction

¹ This perspective considers the distribution of pronunciations associated with a letter pattern: in a highly consistent word, many other existing words containing the same letter pattern are pronounced similarly (for instance, the graphemes "UST" are always pronounced with the same phonemes in MUST, DUST, COMBUST). In an inconsistent word, many existing words are pronounced differently giving rise to conflicting pronunciation (for instance HAVE is inconsistent, because the graphemes "AVE" are pronounced differently in GAVE, WAVE or BEHAVE) (Glushko, 1979). According to this view, a word may be regular because its graphemes are pronounced according to the rule (for instance, DIVINE), but inconsistent if one or more other words containing the same letter pattern are pronounced differently (for instance RAVINE) (Cortese and Simpson, 2000; Gimenes et al., 2020). Irregular words, on the other hand, are usually inconsistent. Both regularity and consistency have been demonstrated as having independent effects in behavioral data (Balota et al., 2006; Cortese and Simpson, 2000).

(words are either regular or irregular) (Chateau and Jared, 2003; Cortese and Simpson, 2000; Yap and Balota, 2009). Here we consider a word as irregular if it includes at least one grapheme that is pronounced differently than the typical rule. Because irregular words cannot be read aloud through orthography-to-phonology conversion processes, most cognitive models of reading consider that they rely on direct mappings from orthography to whole-word forms (e.g., DRC model, Coltheart et al., 2001; PDP model, Plaut et al., 1996; PDP + model, Perry et al., 2007). Regular words to the contrary, might be read with both the non-lexical and the lexical pathway, the latter being increasingly engaged with reading development (Share, 1995) and modulated by orthographic transparency of a language (Das et al., 2011; Lallier and Carreiras, 2018; Ziegler and Goswami, 2005). Opaque (or deep) orthographies (like English), that contain many exception words and inconsistent mappings, tend to rely more on lexical recognition processes than transparent or shallow orthographies (like Italian) in which GPC are regular and consistent (Buetler et al., 2015; De León Rodríguez et al., 2016; Rau et al., 2015). Interestingly, in bilinguals, the orthographic context in which letter-strings appear (deep or transparent language) influence the reading pathway that is selected for reading (Buetler et al., 2015). Contrasting word recognition processes for regular and irregular words in French, as we do here, might thus shed light on a potential switch between reading strategies within the same language for words relying on different routes. Given that the characteristics of dyslexia are themselves modulated by orthographic transparency, deficits being more pronounced in opaque orthographies, and less detected in transparent orthographies (Martin et al., 2016; Ziegler et al., 2001), the regular/irregular contrast is relevant for further characterizing this disorder.

These two different processes at the cognitive level are distinguished at the brain level in a dorsal and a ventral route in the left hemisphere (Cohen and Dehaene, 2009; Jobard et al., 2003; Levy et al., 2009; Pugh et al., 2001). The first non-lexical dorsal route includes the parietal lobe (PL), superior temporal gyrus (STG) and posterior inferior frontal gyrus (IFG) and subserves orthographic-to-phonological conversion. It is activated when reading pseudowords, but also regular and highly frequent words (Levy et al., 2009). The second lexical ventral route involves the ventral occipito temporal cortex (vOTC), the anterior temporal lobe (ATL) and the anterior IFG (Oliver et al., 2017; Pugh et al., 2000; Schlaggar and McCandliss, 2007). To account for regularity effects at the behavioral level (slower performance for irregular words), the DRC model (Coltheart et al., 2001) considers that only irregular words generate conflicting pronunciations from the two routes triggered in parallel, leading to slower processing (Coltheart et al., 2001). In line with this view, neuroimaging studies show that irregular words are distinguished from regular ones mainly in an increased recruitment of phonological regions (IFG) or the angular gyrus (AG) involved in conflict resolution (Binder et al., 2005; Bolger et al., 2008; Tan et al., 2001). Some authors have also found an involvement of the anterior temporal lobe (ATL) and semantic processing in reading irregular words (Binder et al., 2005; Hoffman et al., 2015; Woollams et al., 2011), that rather supports the PDP connectionist model of reading (Harm and Seidenberg, 2004; Plaut et al., 1996) which assumes the involvement of a semantically mediated process (O-S-P) coming in support for reading irregular words that would give rise to an error with the direct O-P route (Harm and Seidenberg, 2004; Plaut et al., 1996).

In the context of our FPVS-EEG oddball paradigm, we do not measure the neural response to regular/irregular words *per se*, but a differential response between base and oddball stimuli. Therefore, when words are presented in streams of pseudowords that recruit the dorsal orthography-to-phonology route, we expect that regular words will give rise to lower levels of contrast than irregular words in typical readers. Indeed, the former may be processed by both lexical and sublexical mechanisms (Coltheart et al., 2001), while the latter can be processed *only* by lexical mechanisms (or supported more strongly by semantics in PDP models), and should therefore be more distinct from *PW*. In *DYS*,

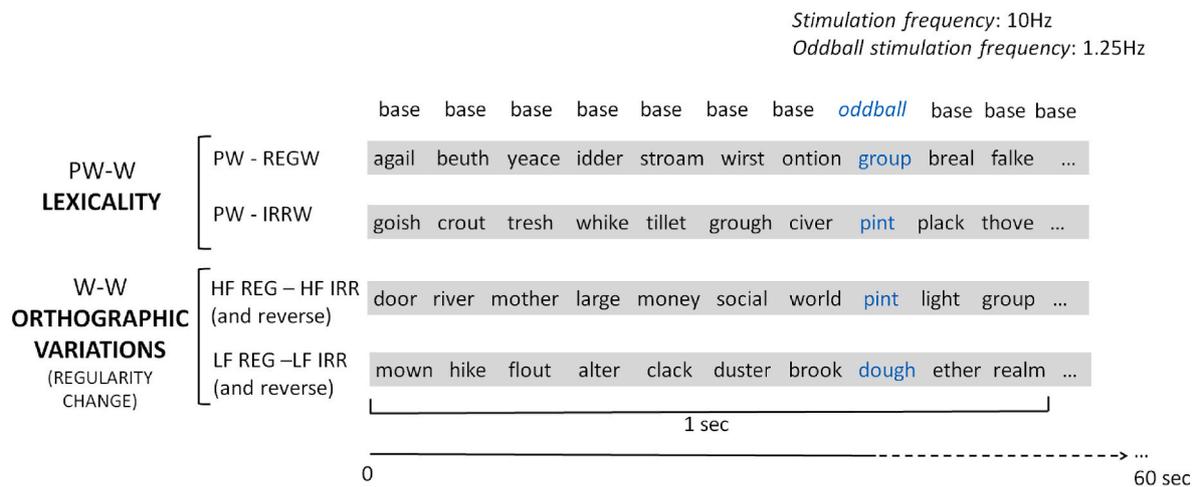


Fig. 1. Experimental EEG design. Stimuli were presented through sinusoidal contrast stimulation at 10 Hz (i.e., every 100 ms), with a deviant category every 8 base stimuli, thus at 1.25 Hz. Four different conditions were tested. For lexicality change (first two rows), regular or irregular words were presented among matched pseudowords (PW-REGW; PW-IRRW). For orthographic variations (sensitivity to regularity change, last two rows), only words were presented: high frequency words (HF) where base stimuli were regular (REG), and oddballs were irregular (IRR) (or the reverse) and low frequency words (LF) where base stimuli were regular, and oddballs were irregular (or the reverse). The examples are illustrations only, as the experiment was done in French language.

the hypothesized phonological core deficit in this population (underspecified or less accessible representations, e.g., Boets et al., 2013; Ramus et al., 2003; Ramus and Szenkovits, 2008) could induce a different pattern of responses than typical readers. Indeed, their deficit is thought to affect the orthography-to-phonology conversion route so that these high functioning adults could have developed compensatory memory-based mechanisms, as described in adults with rudimentary literacy skills who display good performance in reading irregular words despite poor decoding skill (in English: Greenberg et al., 2002; in French: Kolinsky and Tossonian, 2023). In this case, dyslexic individuals could rely similarly on lexical processes for words, irrespective of their regularity, therefore showing similar responses to regular or irregular words.

Third, we wanted to assess the sensitivity and automatic detection of regularity *per se* and its modulation by lexical frequency. For this, we designed stimulation sequences in which base and deviant stimuli differed only on this factor. In such sequences, all presented items are real words, and base/deviant stimuli are distinguished as being regular or irregular (Fig. 1). Therefore, if a response is observed at the deviant frequency, it must reflect the brain's ability to detect a change in regularity between base and deviant words. As for lexical frequency, regularity and consistency effects are greater and sometimes reported only on low-frequency words in behavioral studies (regularity x frequency: Andrews, 1982; Seidenberg et al., 1984; consistency x frequency: Cortese and Simpson, 2000; Jared, 1997; Jared and Seidenberg, 1990). However, this finding is challenged by the fact that many lexical variables correlate with each other (for instance low-frequency words might also have less orthographic neighbors) and, when controlled for, consistency effects have also been reported for high-frequency words (Yap and Balota, 2009). Here, we aimed at assessing and comparing high-frequency words and low-frequency words, matched in neighborhood size, in order to investigate whether the detection of regularity changes is affected by lexical frequency. Therefore, half of the sequences displayed only high frequency words that differed in regularity, and the other half displayed only low frequency words that differed in regularity. We hypothesized a greater sensitivity to regularity change in low-frequency words than in high-frequency words. However, given that regularity or frequency effects are affected by the nature of the task in behavioral studies (e.g., regularity effects emerge mainly in reading aloud, but less so in lexical decision (Seidenberg et al., 1984; Balota and Chumbley, 1984; Yap and Balota, 2009) and that words do not have to be read aloud, or even judged as being words in our paradigm, it is also

possible that regularity effects do not emerge at all during stimulation sequences. In that case, the word-selective response to regular vs. irregular words, or sensitivity to regularity among words, may not differ significantly in either group.

2. Methods

2.1. Participants

Twenty-eight French-speaking higher-education undergraduate students from UCLouvain were retained to participate in this study, half of whom formally diagnosed with dyslexia (8 F/6M, mean age = 19.7, SD = .85; N years at university = 1.69; vocabulary score = 22). They were recruited through a clinical service in speech-therapy at the Faculty of Psychology (*Consultations Psychologiques Specialisees en Psychologie*). The other half of participants were typical readers selected to match dyslexic individuals on age and number of years of education (9F/5M, mean age = 21; SD = 1.3 N years at university = 1.64; vocabulary score = 24) and were retained in the study if they performed within the norms on reading assessment (3 participants were excluded because they scored <2.5SD from the norm in more than 2 reading tests). All participants reported having normal or corrected-to-normal vision and hearing. They had no history of neurological disorders and no comorbid diagnosis of attention disorders. The sample size of two groups of N = 14 matches those used in previous studies using the same sensitive FPVS approach that have consistently reported clear statistically significant effects (Lochy et al., 2015), N = 10; (Liu-Shuang et al., 2014), N = 12 (Rossion et al., 2015), N = 15). All participants underwent behavioral and EEG testing after giving their informed consent for a study that was approved by the local ethical committee (Biomedical Ethical Comity, UCLouvain). The behavioral testing consisted in standardized reading tests (detailed in the material and procedure section) that confirmed the reading difficulties of DYS. For word list reading, they differed from TR in reading times for all categories (see Table 1), for text reading, they differed both in accuracy and response time, as well as for visuo-attentional measures.

2.2. Reading tasks and background testing

We assessed reading ability with reading aloud tasks (see Table 1). In the first task (Phonolec; Plaza et al., 2008), participants had to read short and long pseudowords (PW, max 40: short PW had an average of 5.4 letters (from 4 to 7), with 7/20 monosyllabic and 14/20 bisyllabic

Table 1
Reading tasks scores per group (individuals with dyslexia, typical readers).

Reading task	INDIVIDUALS WITH DYSLEXIA (DYS)	TYPICAL READERS (TR)	t-value (DYS-TR) (df = 25)	p-value
PW score (max 40)	33.31	34.78	1.132	.134
PW - time (sec)	63.34	41.54	-5.872	<.001
REG words score (max 60)	59.62	59.93	(df: 15,7102) = 1.614	.063
REG words -time (sec)	39.36	29.20	-4.061	<.001
IRR words score (max 20)	19	20	(df: 17.152) = 1.504	.075
IRR words -time (sec)	16.17	9.67	-6.954	<.000
Alouette N. Errors	9.85	4.93	(df: 21.265) = -3.071	.003
Alouette -time (sec)	125.15	84.43	-7.616	<.001
Alouette efficiency score	373.08	562.52	7.706	<.001
VA span (composite score, Evadys)	4.69	5.14	2.514	.009

Note: Mean scores are provided for each task as well as reading times. The value of the t-test is provided (degrees of freedom = 25 when equal variances are assumed, else, the corrected degrees of freedom is given in parentheses). The last column indicates the p-value (one-sided) and is written in bold when significant. PW: pseudowords; REG: regular words; IRR: irregular words; VA: visuo-attentional.

stimuli. Long PW had an average of 9.4 letters (from 8 to 11), 2/20 were bisyllabic, 15/20 contained 3 syllables and 3/20 contained 4 syllables), regular words (REG, max 60 : 30 short and 30 long words) and irregular words (IRR, max 20). In the second task, participants were asked to read a meaningless text (Alouette; Lefavrais, 2005). This test is a sensitive and specific screening tool for French adults with dyslexia (Cavalli et al., 2018). It is timed and the participant is stopped after 3 min. A synonym-choice task from the Mill Hill Vocabulary Scale (Raven and Deltour, 1993) was also proposed. This task, of increasing complexity, provides information in terms of the extent and precision of the participants' vocabulary. Finally, participants performed a standard visuo-attentional task on 6 letter-sequences (EVADYS, Valdois et al., 2017).

Table 2
Stimuli characteristics.

	Pseudowords		REGULAR words		IRREGULAR words		Statistics
	matched to HF REGW	matched to HF IRRW	HF	LF	HF	LF	
N (Half 5 and 6 letters)	20	20	20	20	20	20	
N. orthog. neighbors	.95 (.19)	.75 (.23)	1.05 (.17)	.95 (.19)	.9 (.43)	.7 (.19)	F(5,95) = .294; p = .915
Summated bigram	11548 (1001)	11801 (734)	10824 (767)	12436 (1024)	12091 (1534)	10090 (1086)	F(5,95) = .729; p = .603
Frequency							
Lexical Frequency (per million)			58.18 (10.34)	2.14 (.39)	62.86 (17.09)	1.98 (.37)	F(3,57) = 10.729; p < .001 Bonferroni pairwise comparisons: F/NF for REG W: p < .013 F/NF for IRR W: p < .001 REG/IRR for HF: p = 1 REG/IRR for LF: p = 1

Note: Mean and standard errors are given for each variable. 20 items were built in each stimulus type (10 with 5 letters and 10 with 6 letters) in order not to differ in overall number of orthographic neighbors or bigram frequency. Pseudowords were constructed to match high frequency words only, as they were presented only with those words. Lexical frequency did not differ between regular/irregular words within each HF/LF category, and differed significantly between HF/LF words, in each regular/irregular category. HF: high-frequency, LF: low-frequency; REGW: regular words, IRRW: irregular words.

2.3. EEG testing stimuli

French words were selected to create 4 sets of 20 items (Table 2; half 5-letters and half 6-letters long): high-frequency regular (HFR), high frequency irregular (HFI), low frequency regular (LFR), low frequency irregular (LFI) words. The high/low frequency sets did not differ in regularity but differed in frequency (computed as frequency per million); the regular/irregular sets did not differ in frequency but differed in regularity. The four sets did not differ in summated bigram frequency and number of orthographic neighbors (i.e., number of existing words of the same length by changing one letter of the target word). Characteristics of the stimuli were extracted with WordGen (Duyck et al., 2004) based on the LEXIQUE database for French (Table 2).

Pseudowords were created to match high frequency words item-wise on consonant-vowel structure, bigram frequency, and number of orthographic neighbors.

In total, we thus had 2 sets of 20 pseudowords, and 4 sets of 20 words (see Appendix A). These sets were used to create sequences contrasting: pseudowords to HF regular words (PW-HF REG), pseudowords to HF irregular words (PW-HF IRR), HF irregular words to HF regular words (HF: IRR-REG), and LF irregular words to LF regular words (LF: IRR-REG).

2.4. Procedure

Behavioral and EEG testing occurred in two different sessions of approximately 2 h each.

During the first session, participants underwent behavioral testing consisting of the reading tasks, the VA span task, and vocabulary assessment. Task order was blocked.

The reading-aloud tasks for single items (Phonolec, Plaza et al., 2008) were computer-based: the words or pseudowords appeared in columns on the screen and the participant had to read them as quickly as possible. Therefore, a measure of accuracy rate (proportion of correct answers) and speed (reading time) was collected for each type of item.

The meaningless text-reading (Alouette; Lefavrais, 2005) consisted in presenting the text on a sheet of paper, allowing 3 min of reading for each participant. The experimenter wrote down the errors and self-corrections. Reading time and accuracy were taken into account. A reading efficiency score, considering both speed and accuracy, was also calculated ((C X 180)/T, where C is the number of words correctly read and T is the time taken to read the text). A higher score corresponds to a better performance.

The Mill Hill Vocabulary Scale (Raven and Deltour, 1993) is a synonym judgment task containing 34 target words. The target was written in upper-case, and participants had to underline the synonym word

among 6 choices presented in lower-case. There was no time limit.

Finally, the visuo-attentional EVADYS task (Valdois et al., 2017) is a standardized computerized test, where a sequence of 6 letters was presented on screen (after presentation of a central fixation point). In the “global report” condition, the participant was asked to recall orally the sequence of letters presented. In the “partial report” condition, a vertical line appeared under a letter (after the sequence has disappeared from the screen) and the participant had to recall the indicated letter. The composite score is the average of the global and partial report scores.

EEG testing took place during the second session. Participants were comfortably seated in front a computer screen where they watched 30 sequences of stimuli while EEG was recorded.

Stimuli were presented at a size of 238×71 pixels (3.97×1.26 degrees of visual angle at a distance of 1m) on a 120 Hz refresh rate monitor. Each stimulation sequence started with 2 s of fade-in, lasted 60 s, and ended with 2 s of fade-out. The stimulation sequences consisted of a stream of visual stimuli (letter-strings) presented at the frequency $f = 10$ Hz (100 ms SOA), contrasting two categories of stimuli: a frequent one (base stimuli) and a deviant one (deviant stimuli). Deviant stimuli appeared every 8th item (e.g., BBBBDBBBBBBDB ...), i.e., at a periodic frequency f/n of 10Hz/8, 1.25 Hz or every 800ms. We contrasted different categories of stimuli (see Fig. 1). For assessing lexicality, base stimuli consisted of PW and deviant stimuli consisted of frequent words that were either regular (PW/HF-REG), or irregular (PW/HF-IRR). For assessing sensitivity to regularity changes among words, 2 conditions were used: words were either high frequency words varying in regularity (i.e., HF-REG/HF-IRR and the reverse), or low frequency words varying in regularity (LF-REG/LF-IRR and the reverse). There were therefore 6 different types of sequences, that were all repeated 3 times in random order, for a total of 18 sequences.

2.5. EEG acquisition and preprocessing

EEG was acquired in a quiet room of the University at 1024Hz using a 68-channel Biosemi Active II system (Biosemi, Amsterdam, Netherlands), with electrodes including 64 channels standard 10–20 system locations (<http://www.biosemi.com>) plus a row of 4 posterior electrodes including PO9, I1, I2, PO10. The magnitude of the offset of all electrodes, referenced to the common mode sense (CMS), was held below 50 mV. EEG analyses were carried out using Letswave 6 (<https://github.com/NOCIONS/letswave6>), and Matlab 2016 (The Mathworks). After FFT band-pass filtering between .1 and 100Hz, EEG data were segmented to include 2 s before and after each sequence, resulting in 64-s segments (−2 – 62 s), for visualization purposes, and then resampled to 512Hz to reduce file size and data processing time. Artefact-ridden or noisy channels were replaced using linear interpolation (on average, 1.56 % of channels). All channels were re-referenced to the common average. EEG recordings were then segmented again from stimulation onset until 60 s, corresponding to the largest number of complete cycles of 800 ms (75 cycles) at the 1.25Hz frequency within the stimulation period.

The data were analyzed following the same procedure as in previous studies with similar paradigms (e.g. (Liu-Shuang et al., 2014; Lochy et al., 2015, 2016; Retter and Rossion, 2016; Rossion et al., 2015), but is nevertheless detailed here.

2.6. Data analysis

The three repetitions of each stimulation sequence were averaged per condition in the time domain, for each participant, to increase SNR. A Fast Fourier Transform (FFT) was applied to the averaged time-window, and normalized amplitude spectra were extracted for all channels. This yielded EEG spectra with a high frequency resolution (1/60 s = 0.016Hz), increasing SNR and allowing objective identification of the response at the exact frequencies of interest (i.e., $f = 10$ Hz for the base stimulation rate and $f/n = 1.25$ Hz and harmonics ($2f/n$, $3f/n$, etc)

for the deviant stimulation; see Fig. 2).

Given that the response of interest occurs into a strictly defined frequency bin (related to stimulation frequency), surrounding bins are considered as noise, or baseline. The latter is defined as the 20 surrounding bins of each target bin, excluding the immediately adjacent and the extreme (min and max) bins (Liu-Shuang et al., 2014; Rossion et al., 2015; Srinivasan et al., 1999). We then computed three indices. First, the signal-to-noise ratio (SNR, see Fig. 2) was estimated across the EEG spectrum, by dividing the amplitude at each frequency bin by the average amplitude of 20 surrounding bins (10 on each side; Liu-Shuang et al., 2014). Second, given that the amplitude at any given frequency is considered as a combination of signal and noise (Heinrich et al., 2009), the average voltage amplitude of the 20 surrounding bins (i.e., the noise) was subtracted out (Retter and Rossion, 2016) to quantify the responses of interest in microvolts. Finally, periodic stimulation typically generates EEG responses at the stimulation frequency (f , e.g., 10 Hz) and harmonics at integer values of the stimulation frequency ($2f$, i.e., 20 Hz; $3f$, i.e., 30 Hz; etc.) (Norcia et al., 2015; Regan, 1989). All harmonics, not only the fundamental or first harmonic f , contribute to the EEG response and should be considered in the analysis of the response (Retter et al., 2021; Retter and Rossion, 2016). To determine how many harmonics to consider both for the base rate response (10 Hz, 20 Hz, etc.), and the deviant response at $f/8$ (1.25 Hz, 2.50 Hz, 3.75 Hz, etc.), Z-scores ($Z(x) = x - \text{mean}(\text{noise}) / \text{SD}(\text{noise})$) were computed per group on the raw (uncorrected for baseline EEG noise) amplitudes, and considered significant if larger than 2.33 ($p < .01$, one-tailed, signal > noise).

2.6.1. Base rate responses

Visual inspection (Fig. 3) and Z-scores showed base rate responses mainly in a medial-occipital region encompassing (Oiz, Oz, Iz, O2, POI1, POOz, POI2, O1). On these electrodes, 4 harmonics were significant independently of group or condition (from 10Hz to 40Hz).

2.6.2. Word-selective responses

Z-scores revealed significant responses on several harmonics in both groups with a left occipito-temporal topography around electrode P9 (see Figs. 2 and 3) in agreement with previous studies in adults (Lochy et al., 2015, 2024) or in children (Lochy et al., 2016; Lutz et al., 2024; van de Walle de Ghelcke et al., 2021). We grouped electrodes into an occipito-temporal region (OT) in the left hemisphere (LOT: P7, P9, PPO5, PO7, PO9, PO11) and their homologous in the right hemisphere (ROT: P8, P10, PPO6, PO8, PO10, PO12). These electrodes displayed significant responses ($Z > 2.33$) on 4 to 6 harmonics (from $2f/n$ (2.5Hz) to $6f/n$ (7.5Hz)). In both regions, we summed the baseline corrected amplitude values of 6 harmonics (from 1.25Hz to 7.5Hz), given that it was the highest number of significant harmonics (albeit in the typical readers group).

3. Results

We present the results from a broader to a finer level decomposition.

First, we perform an analysis at a general level (Section 3.1, Fig. 3), to compare the neural responses of dyslexics and typical readers broadly for the detection of words among PW (lexicality) and detection of regularity variations among words. We also contrast dyslexic and typical readers on their responses at the base rate (general visual response).

Second, we analyze the discrimination responses at a fine-grained level within lexicality (Section 3.2.1, Fig. 4) and regularity variations among words (Section 3.2.2., Fig. 5). For lexicality (words among PW), we examine the effect of word regularity (regular vs irregular words inserted in pseudowords). For sensitivity to regularity variations (regular vs irregular words), we examine the effect of lexical frequency (HF words vs LF words containing regularity changes).

Finally, we explore brain-behavior correlations (Section 3.2.3).

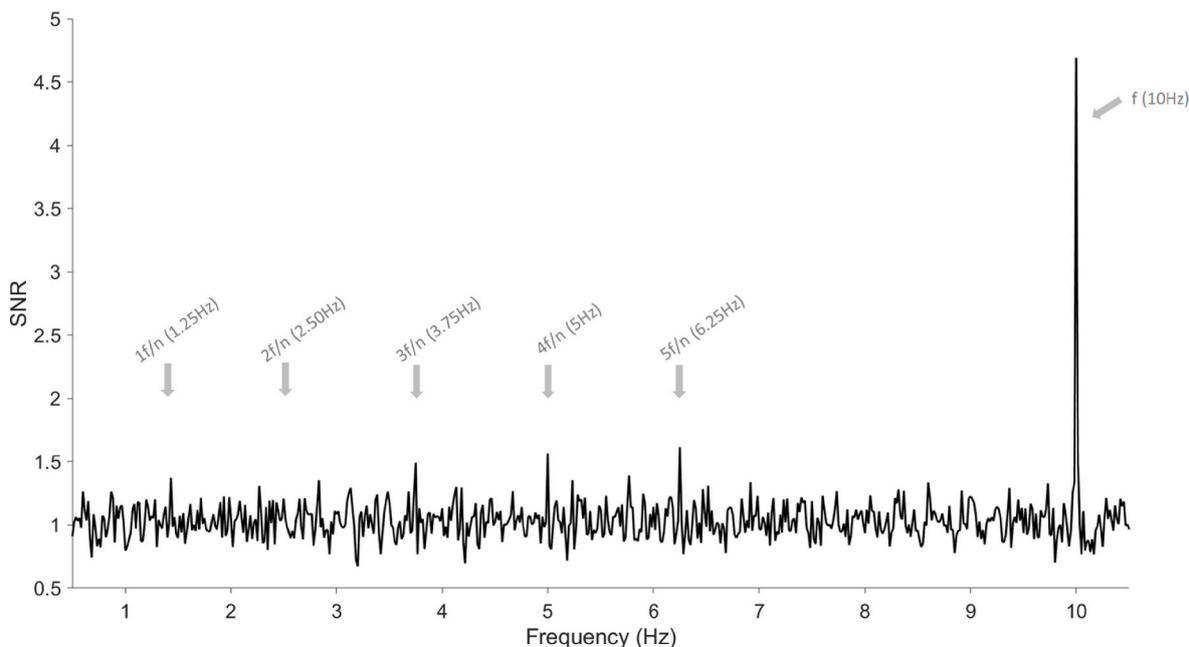


Fig. 2. Example of a SNR response spectrum in the left occipito-temporal ROI (here for the group of typical readers in the condition with pseudowords as base stimuli, and irregular words as deviant stimuli). The SNR values are plotted in the frequency domain for the left occipito-temporal region-of-interest (chance level is at 1). Responses at the general visual stimulation frequency or base rate occur at f (10Hz) and harmonics ($2f$, $3f$, ..., not visible on this spectrum). Responses at the oddball frequency f/n of the deviant stimuli occur at 1.25Hz and harmonics (on this spectrum, visible up to 6.25Hz). SNR serves visualization purposes. Quantification is performed on baseline-corrected amplitudes (in μ V, see text) after summing the significant harmonics, as determined with a Z-score calculation (see text).

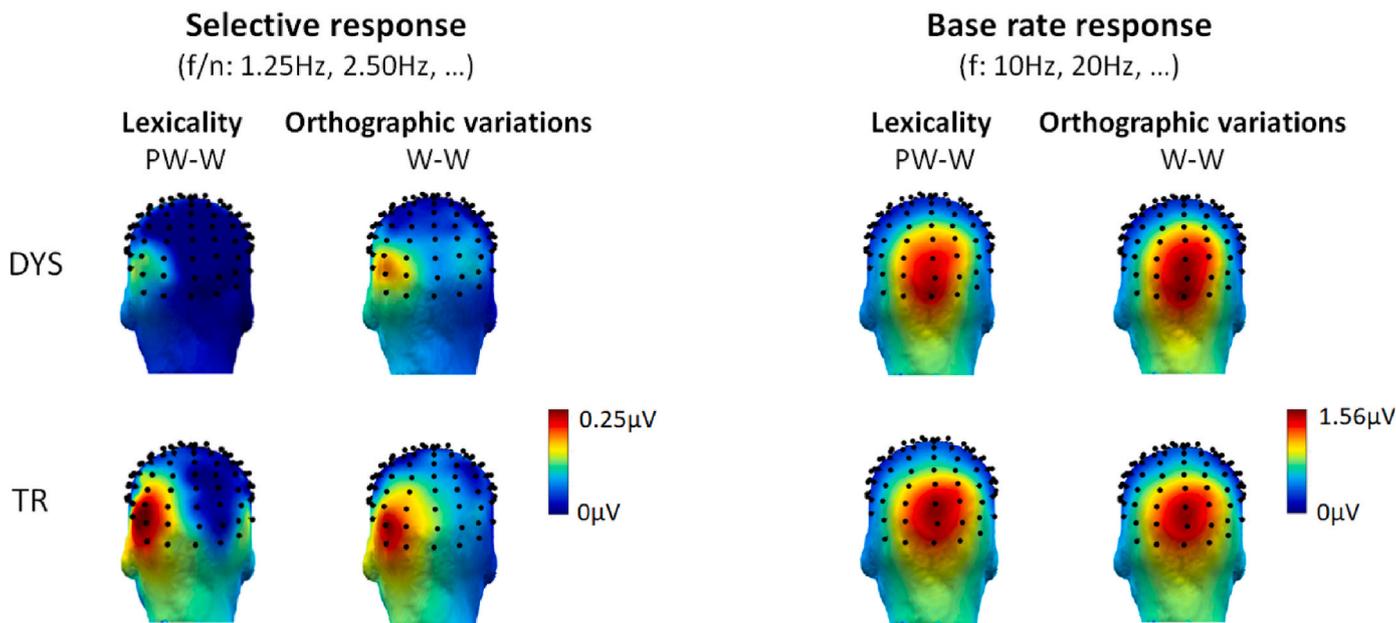


Fig. 3. Topographies for the general analysis of lexicity and orthographic variations. Response amplitudes are plotted on a 3-D scalp map for selective discrimination responses (1.25Hz and harmonics) and base rate responses (10Hz and harmonics) for each group (dyslexics: DYS, typical readers: TR) per variation type. The left side of the figure shows selective responses for lexicity change (pseudowords-words) and orthographic regularity variations (words among words). On the right panel, base rate responses are displayed (overall stimulation of 10Hz) in the two variation types. Dyslexic and typical readers displayed similar base rate responses.

3.1. General level analysis: sensitivity to lexicity (PW-W) and orthographic regularity (W-W)

For oddball responses, we analyzed the sum of 6 significant harmonics with an ANOVA 2 Hemispheres (LOT, ROT) x 2 Variation Type (Lexicity, Regularity Variation) x 2 Groups (Dyslexics, Typical readers), with repeated measures on the first two factors.

There was a main effect of Hemisphere, $F(1,25) = 22.552; p < .001; \eta_p^2 = .474$, with stronger left hemisphere responses (LH: $M = .16 \mu$ V, $SD = .03 \mu$ V; RH: $M = .06 \mu$ V, $SD = .02 \mu$ V). There was no main effect of Group, $F(1,25) = 2.500; p = .126; \eta_p^2 = .091$, but an interaction between Variation Type and Group, $F(1,25) = 4.774; p = .038; \eta_p^2 = .160$. For lexicity, DYS differed from TR, $t(25) = -2.259; p = .016$; 1-tailed, displaying lower response amplitudes (DYS: $M = .02 \mu$ V, $SD = .04 \mu$ V

vs TR: $M = .15 \mu\text{V}$, $SD = .04 \mu\text{V}$) while for regularity variations among words, they showed similar response amplitudes, $t(25) = .055$; $p = .478$; DYS: $M = .11 \mu\text{V}$, $SD = .03 \mu\text{V}$ and TR: $M = .11 \mu\text{V}$, $SD = .03 \mu\text{V}$ respectively. No other interaction was significant.

By contrast, the analysis of responses at the base rate (MO-ROI containing 8 best electrodes) with an ANOVA 2 (Variation type: lexicality vs orthographic) x 2 (Groups: DYS/TR) showed no effect of Variation Type, $F(1,25) = 1.207$; $p = .282$; $\eta_p^2 = .046$, no effect of Group, $F(1,25) = .002$; $p = .961$; $\eta_p^2 = .000$ and no interaction, $F(1,25) = 2.399$; $p = .134$; $\eta_p^2 = .088$.

3.2. Fine-grained level analysis: discrimination responses by variation type

3.2.1. Lexicality (words in pseudowords): effect of regularity

A rapid visual inspection of the data (Fig. 4) suggests not only weaker responses in dyslexic individuals than in typical readers overall (as revealed with the results of the above section), but also lower responses

for regular words than irregular words, in both groups.

We ran an ANOVA with Hemisphere (LH/RH) and Regularity (regular/irregular words) as repeated factors and Group (dyslexics/controls) as a between-subjects factor. Results show a significant main effects of Regularity, $F(1,25) = 5.765$; $p = .024$; $\eta_p^2 = .187$, (irregular words: $M = 0.14 \mu\text{V}$, $SD = .04 \mu\text{V}$; regular: $M = 0.03 \mu\text{V}$, $SD = .03 \mu\text{V}$), of Hemisphere, $F(1,25) = 17.630$; $p < .0001$; $\eta_p^2 = .414$, as well as a main effect of Group, $F(1,25) = 5.103$; $p = .033$; $\eta_p^2 = .170$ (DYS: $M = 0.03 \mu\text{V}$, $SD = 0.04 \mu\text{V}$; TR: $M = 0.15 \mu\text{V}$, $SD = 0.04 \mu\text{V}$). Overall, dyslexics differed from typical readers by displaying weaker responses, but the pattern of responses was similar in both groups as revealed by the lack of interaction, with stronger responses for irregular than for regular words (Fig. 4A).

Since responses of dyslexic individuals were very weak for REG words (see Fig. 4A and B) that we also computed t-tests to assess their significance against noise-level (i.e., 0 μV). While typical readers displayed responses significantly different from 0 in both cases, $t(13) = 3.147$; $p < .008$ for irregular; and $t(13) = 2.628$; $p < .021$ for regular words, responses were significantly different from 0 only for irregular

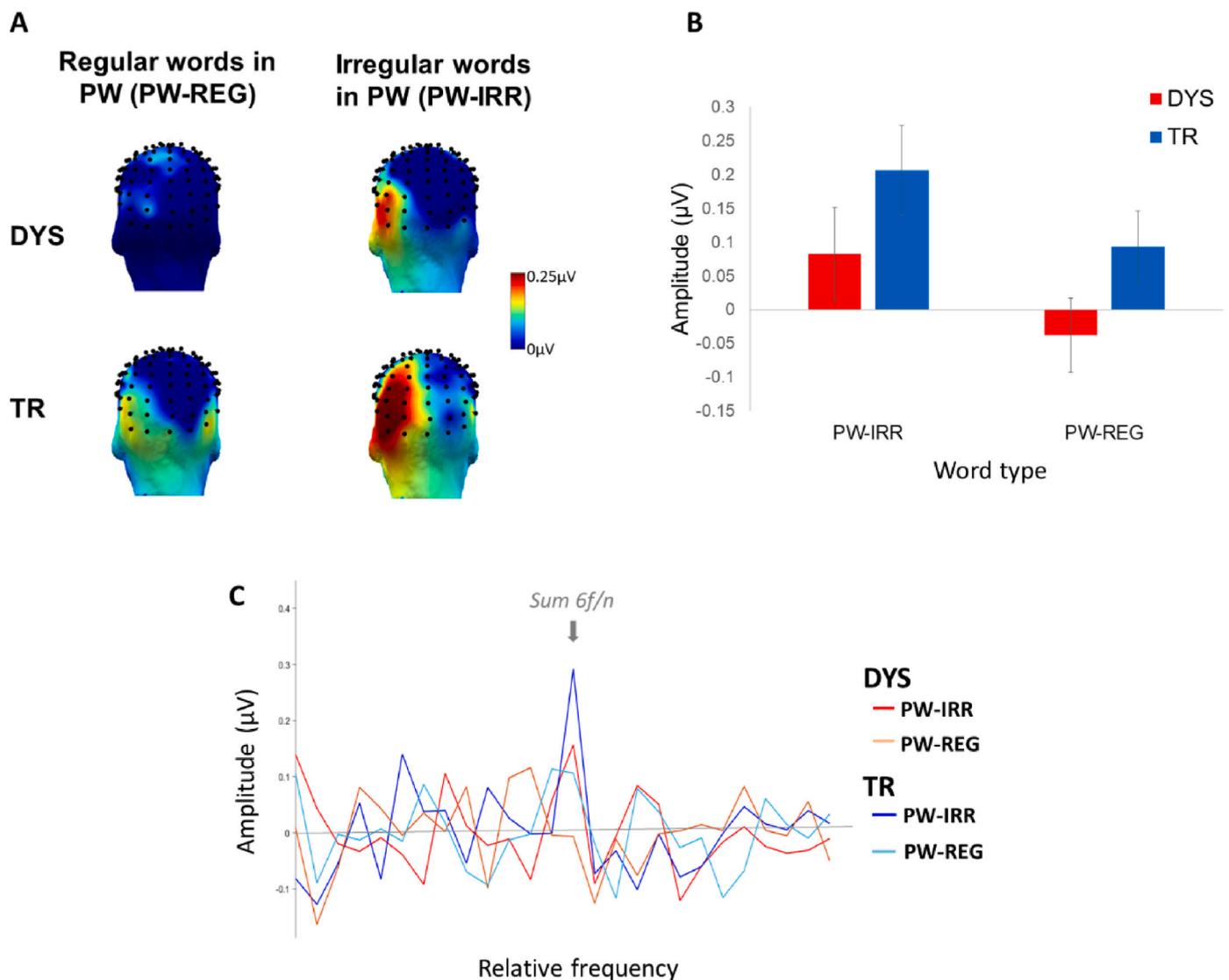


Fig. 4. Lexicality effect as a function of word type (regular, irregular) and groups. **A.** Scalp topographies per word type for the discrimination response (1.25Hz and harmonics). **B.** Response amplitudes in the OT ROI. Dyslexics (red bars) show overall weaker responses than typical readers (blue bars) but both groups have stronger discrimination responses when irregular words, rather than regular words, are inserted in streams of pseudowords. Dyslexics, however, do not have any significant discrimination response for regular words among PW (right column). **C.** Response spectrum displaying responses to words among pseudowords for dyslexics and typical readers, as a function of contrast type (irregular or regular words). In this display, the amplitude represents the sum of significant harmonics of word-selective responses and is displayed as the central bin, with 10 bins on each side. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

words in dyslexics, $t(12) = 2.948$; $p < .012$ (regular words: $t(12) = .260$; $p = .799$). At the individual level, 12/13 dyslexics had near-zero values of amplitude ($<0.02 \mu\text{V}$; $N = 2$) for regular words among PW, while only 4/14 normal readers showed this profile.

3.2.2. Orthographic variations: detection of regularity changes among words

Here we compare only the discrimination of words within streams of other words, that varied in regularity. Regular words were inserted in irregular ones or the reverse, and all words within a sequence were either frequent (HF) or non-frequent (LF) (see Fig. 1). Neural responses to deviant stimuli, measured in amplitudes (μV), thus represents the sensitivity to the change in regularity among base/deviant words (Fig. 5).

On these amplitudes, we computed an ANOVA with 2 Hemispheres (LH, RH) x 2 Frequency Type (HF, LF words) as repeated measures and Group as between-subjects factor. There was only a main effect of Hemisphere, $F = 12.326$; $p = .002$; $\eta_p^2 = .330$, with stronger responses in the LOT ($M = 0.16 \mu\text{V}$, $SD = 0.03 \mu\text{V}$) than in the ROT ($M = 0.06 \mu\text{V}$, SD

$= 0.02 \mu\text{V}$). There was a trend for an effect of Frequency Type, $F = 3.819$; $p = .062$; $\eta_p^2 = .133$, because the sensitivity to regularity change was two times stronger in LF words ($M = 0.15 \mu\text{V}$, $SD = 0.03 \mu\text{V}$) than in HF words ($M = 0.07 \mu\text{V}$, $SD = 0.03 \mu\text{V}$), as expected if frequent words (regular/irregular) are mostly processed with the lexical route. There was no effect of Group ($p = .956$) and no other interaction.

In each group, t -test against $0 \mu\text{V}$ confirmed that regularity changes were detected in HF/LF words, but only in the left hemisphere (HF words: DYS: $t(12) = 2.323$; $p = .019$; TR: $t(13) = 3.008$; $p = .005$; LF words: DYS: $t(12) = 3.411$; $p = .003$; TR: $t(13) = 3.348$; $p = .003$).

3.2.3. Brain-behavior correlations

Text reading time correlated negatively with response amplitudes for PW-REG ($Rho = -.43$; $p = .012$) (Fig. 6, left panel), although reading times for lists of unrelated words did not correlate with response amplitudes, neither for regular words reading with PW-REG ($Rho = -.11$; $p = .29$) nor irregular words reading with PW-IRR ($Rho = -.25$; $p = .10$).

To assess the reliance on the phonological route, we computed for each participant an index of the sensitivity to length in PW reading, as

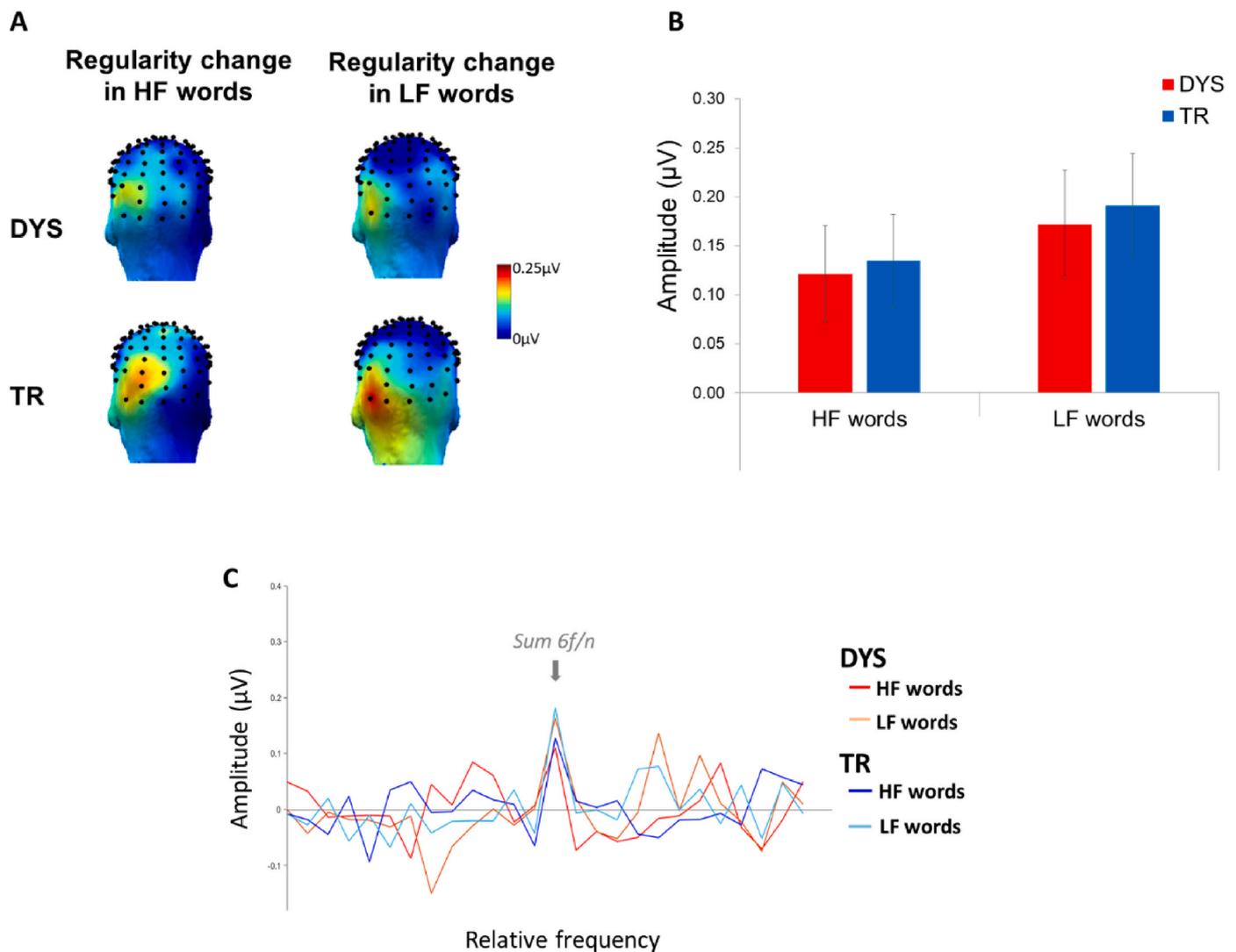


Fig. 5. Sensitivity to regularity changes among words. Words are presented among words, and they differ in regularity (deviant words are regular among irregular words or the reverse). All words in a sequence are either high frequency words (HF words) or low frequency words (LF words). **A. Response topographies** for dyslexics (DYS) and controls (NR) in detecting regularity changes in sequences of HF words or sequences of LF words. **B. Amplitude of responses** to the deviant (regularity change) in the left occipito-temporal ROI, for HF words and LF words, in dyslexics (red bars) or typical readers (blue bars). **C. Response spectrum** displaying responses to regularity change for dyslexics and typical readers, as a function of word type (HF or LF words). In this display, the amplitude represents the sum of significant harmonics of word-selective responses and is displayed as the central bin, with 10 bins on each side. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

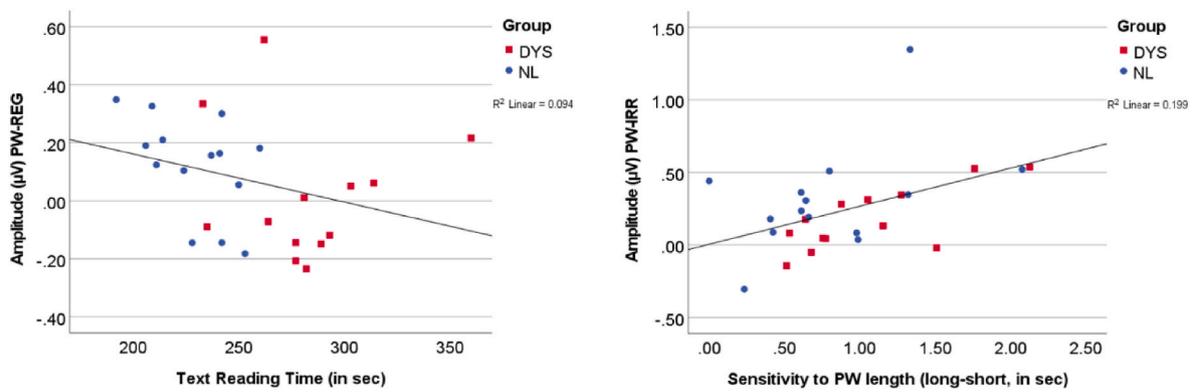


Fig. 6. Brain-Behavior correlations. The left panel shows the relationship between text reading time and response amplitude for regular words among pseudowords: the slower readers (mostly dyslexics, in red) also have the weaker response amplitudes. The right panel plots the correlation between the sensitivity to length in pseudowords reading (difference in time between long and short PW) and response amplitudes. A positive relationship is found between the sensitivity to length, hence a less efficient phonological route, and response amplitudes for irregular words among pseudowords in the LOT (left), hence the reliance on lexical processes when recognizing words. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tested in the standardized behavioral testing (difference in reading times for long ($M = 9.4$ letters, see 2.2.) minus short PW ($M = 5.4$ letters, see 2.2.). This index correlated positively with response amplitudes for PW-IRR in the LOT ($Rho = .42$; $p = .01$; Fig. 6, right panel). It reflects that the more participants are sensitive to length in applying the phonological route (hence, that this route is slower/less efficient), the stronger they detect words processed by the lexical route. Confirming the relationship of this index with lexical processes, a positive correlation was also found with amplitudes in the detection of regularity changes among words, only for LF words ($Rho = .52$; $p = .036$) and not for HF words ($Rho = .24$; $p = .12$).

4. Discussion

Here we used FPVS-EEG to investigate the sensitivity of the visual word recognition system to lexical characteristics of words, mainly their orthographic regularity and lexical frequency, in adults with dyslexia (DYS) and typical readers. The FPVS-EEG approach is advantageous in terms of objectivity (i.e., frequencies of interest are determined a priori) and its high sensitivity allows short testing times with a high SNR (Norcia et al., 2015; Rossion et al., 2020). While this FPVS-EEG approach has proved its sensitivity to assess visual letter and word recognition (in French: Lochy et al., 2015, 2024; Marchive et al., 2025, in German: Aristei et al., 2021); in English: Hauk et al., 2024), its development and neural basis (Lochy et al., 2016; Lutz et al., 2024; van de Walle de Ghelcke et al., 2021), until the present study, it had not been used to compare visual word recognition in individuals with or without developmental dyslexia. Our results highlight lower response amplitudes in DYS than typical readers for words among pseudowords, with no difference in their general visual responses. Together with this expected quantitative difference between the groups, a qualitative difference also emerged: in comparison to typical readers, individuals with dyslexia displayed a specific profile pattern of responses with no measurable discrimination of regular words among pseudowords.

The current study also investigated for the first time the sensitivity of the FPVS approach to contrast word categories that differ at a fine-grained orthographic level (for sensitivity to different semantic categories of words in FPVS-EEG, see Volfart et al., 2021). Here, we show the sensitivity of FPVS-EEG to highlight selective responses to words that differ in regularity, not only among pseudowords but, more impressively, among other words differing only on this factor.

4.1. Quantitative and qualitative difference in dyslexia

Individuals with dyslexia tended to have lower responses overall (see

Fig. 3), although this was significant only for lexical detection (PW-W), not for orthographic variations (W-W). This finding is in line with reduced activation to words in dyslexia in all the left hemispheric ventral and dorsal areas involved in the reading network, irrespective of the neuroimaging method used (for reviews, see Danelli et al., 2017; Kronbichler and Kronbichler, 2018; Maisog et al., 2008; Martin et al., 2015; Richlan et al., 2011). The proposal of a general deficit for rapid processing of visually presented stimuli (Flint and Pammer, 2019; Stein, 2014, 2019), or for neural adaptation in dyslexia (Perrachione et al., 2016) might also play a role here. This impairment at “anchoring” to consistent stimulus statistics would potentially impact their ability to enhance perceptual thresholds (Ahissar et al., 2006; Banai and Ahissar, 2010). In the current paradigm, given that base stimuli are repeated before a deviant stimulus is presented, one could argue that the differential response may reflect both the decreased (adapted) response to the repeated stimulus category, and the increased response to the deviant stimulus category. In the case of dyslexia, both a reduced adaptation to the base stimuli, or a reduced response to the deviant, would give rise to an overall lower differential response. However, while neural adaptation is usually observed when repeating identical stimulus features, stimuli changed substantially at every stimulation cycle here. Finally, even if individuals with dyslexia may struggle with rapid processing of visual stimuli (Kristjánsson and Sigurdardóttir, 2023; Stein, 2019), the two groups do not differ in the overall general visual response at 10 Hz, neither in amplitude nor topography. Thus, it suggests that there was no general attentional, visual, or broad letter-strings processing differences between groups at this rate, supporting the specificity of the pattern found on word-selective responses.

Crucially, we also highlight a qualitative difference between individuals with dyslexia and controls. Among PW, which presumably activate the dorsal route and a decoding strategy, dyslexic individuals do not discriminate regular words. This implies that regular words do not automatically activate lexical processes when the dorsal route is involved by base stimuli (PW). However, irregular words, which cannot be processed by decoding (and were probably also highly trained in intervention setups), were discriminated from PW, presumably recruiting ventral lexical recognition processes. We can be confident that this effect is not due to an overall activation difference in the lexicon, which would be due for instance to a difference in the number of orthographic neighbors activated in each condition, since this factor was matched between regular and irregular words. Furthermore, the lack of lexical discrimination in dyslexic individuals was not all-or-none. When “forcing” the visual word recognition system to activate lexical processes by presenting words as base stimuli, dyslexic individuals displayed discrimination responses according to regularity. This finding can be

understood if we consider that once lexical mechanisms are triggered, words can be normally processed, perhaps with global word recognition processes (Sigurdardottir et al., 2021), but if reading is tuned to sub-lexical decoding, then there is no automatic activation of lexical recognition processes. This is reminiscent of the proposal that the lexical/non-lexical pathways are differentially activated according to orthographic transparency (Das et al., 2011; Lallier and Carreiras, 2018). Note, however, that this proposal is usually discussed in the context of the orthographic depth hypothesis (Frost, 2005; Katz and Feldman, 1983; Katz and Frost, 1992) when comparing languages. Shallow languages, that have regular and consistent GPC, rely more on non-lexical processes than deep languages, where irregular and inconsistent GPC induce a stronger reliance on lexical recognition processes (Buetler et al., 2015; De León Rodríguez et al., 2016; Rau et al., 2015). However, in the present case, this modulation would occur within a language, French.

It might seem surprising that high-performing adult with dyslexia do not exhibit significant responses to regular words among pseudowords, similarly to 5 years-old preschoolers tested with the same FPVS-EEG paradigm (Lochy et al., 2016). However, in these young children, there was a left-lateralized print-selective response for words or pseudowords among unfamiliar non-alphabetic characters, interpreted as reflecting letter familiarity, not decoding, given the total lack of reading ability beyond basic letter knowledge (i.e., no child could read small words). With the young children, the lack of lexical responses thus simply reflected the inability to read or decode. In contrast, dyslexic adults have developed behavioral reading abilities, present lexical responses for irregular words and are even sensitive to regularity changes among words. Thus, it is important to stress that a similar (lack of) result (i.e., no lexical discrimination for regular words in young children and DYS) should be interpreted differently depending on the pattern observed on other conditions and on reading abilities measured behaviorally (e.g., the (in)ability to decode letter strings).

4.2. Selective lexical responses with FPVS EEG

For lexical responses (words among pseudowords), both dyslexic individuals and controls detected words among pseudowords overall, with a general regularity effect, and a left-hemispheric topography. This scalp topography on the left occipito-temporal region is consistent with established brain regions associated with reading and visual word recognition, known to include the left ventral occipito-temporal cortex (VOTC) and more specifically the so-called ‘visual word form area’ (VWFA) (Cattinelli et al., 2013; Dehaene et al., 2005; Schurz et al., 2014; Wandell and Le, 2017). Given the two distinct processing routes for letter-strings that have been proposed, the dorsal and ventral streams (Cohen et al., 2008; Jobard et al., 2003; Levy et al., 2009; Pugh et al., 2001; Yeatman and White, 2021), the observed responses for words within pseudowords (PW) may stem from these different routes being activated by stimulus type. PW engage non-lexical processes, relying more on the dorsal stream (Levy et al., 2009; White et al., 2019; Yeatman et al., 2014), while words predominantly involve the ventral stream (Glezer et al., 2009, 2015; Hirshorn et al., 2016; Pugh et al., 2001; Riesenhuber and Glezer, 2017; Schlaggar and McCandliss, 2007; Yeatman and White, 2021).

Regular words triggered lower response amplitudes than irregular words. Given that PW were built item-wise to match each category of words in consonant-vowel structure, bigram frequency, or neighborhood size, and that both types of words were similarly frequent, this finding shows that unintentional visual word recognition is modulated by regularity (Seidenberg et al., 1984). This finding may be interpreted in different ways. First, in a dual-route perspective acknowledging the existence of an orthographic lexicon for frequent words (Coltheart et al., 2001), this finding suggests that frequent regular and irregular words may be distinguished at input levels: they would be “tagged” differently in the orthographic input lexicon, and several findings now argue for

whole-word orthographic representations in the vOTC itself (Glezer et al., 2009; Glezer et al., 2015). However, since the irregularity lies in the relationship between letters and sounds, not in the arrangement of the letters string *per se*, it would mean that words automatically trigger the corresponding phonological codes (no linguistic task was required from the participants like reading aloud), and that vOTC activation is modulated by rapid feedbacks from top-down phonological information (Price and Devlin, 2011). A slightly different perspective is to consider that the context provided by base stimuli would preferentially activate one or the other reading routes. Indeed, we should recall that our paradigm does not measure an absolute response to words, but a differential response that is potentially influenced by the mechanisms involved in processing the base stimuli. Such context effects on word reading strategies have been also reported behaviorally. In orthographies of intermediate depth, the reliance on decoding vs. lexical processing, assessed by word length or regularity effects, can be influenced by presenting words in mixed vs blocked lists (Content and Peereboom, 1992; Kolinsky and Tossonian, 2023; Lima and Castro, 2010), presumably because the presence of pseudowords engages smaller units of processing also applied to words. In cross-languages comparisons, lists characteristics have also been shown to influence the performance of children in deep orthography, who have to switch between smaller and larger units of processing (for pseudowords and words respectively), but not the performance of children in shallow orthographies (Goswami et al., 2003). Here, we can consider that a stream of (mainly) PW during sequences of 60 s presumably activates brain processes associated with decoding strategies in the dorsal assembly route. In that context of sublexical enhancement, regular words would be partly processed by the same mechanisms as pseudowords (given that they can be read aloud relying on the phonological route), while irregular words would trigger solely lexical processes as they cannot be processed by the assembly route, giving rise to a greater contrast.

Another way to interpret this finding is to consider, in the Triangle Model (PDP) perspective (Plaut et al., 1996), that irregular words induce reliance on the semantically mediated route, while regular words solely rely on the orthography-to-phonology route. In favor of this theoretical proposal, the anterior temporal lobe (ATL) has been found to respond more strongly to exception than regular words in previous studies (Hoffman et al., 2015; Woollams et al., 2014). Our findings would thus reflect the extra involvement of semantic processing for irregular words that would trigger a stronger contrast with PW, while regular words could be processed with the same orthography-to-phonology mechanisms as PW. Nevertheless, in typical readers, regular words are also discriminated, reflecting an activation of lexico-semantic properties in both cases (Taylor et al., 2012).

When only words were presented, and deviants differed from base stimuli only by regularity, our results show that neural discrimination responses are present in both sequence types and tend to be stronger in LF words than in HF words. This parallels behavioral findings of an interaction between regularity and frequency (Jared, 1997; Seidenberg et al., 1984), where regularity effects are stronger for LF words although not totally absent in HF words (e.g., Jared, 1997, 2002; Yap and Balota, 2009). In reading aloud, this interaction is explained by a mismatch between the phonological form generated by different reading mechanisms (lexical vs. conversion routes in DRC models, Coltheart et al., 2001; and semantically mediated vs. orthography-to-phonology processing in the Triangle Model, Plaut et al., 1996). However, these findings have also been shown to be task-dependent and to emerge when phonological codes are triggered, thus in reading aloud but not in semantic or lexical decision for instance, both behaviorally (Balota and Chumbley, 1984) or with ERPs (Fischer-Baum et al., 2014). Thus, here also, our finding that there is discrimination of orthographic regularity suggests rapid feedbacks from top-down phonological information (Price and Devlin, 2011).

4.3. Brain-behavior relationships

Brain-behavior correlations revealed two interesting relationships. First, there was an inverse correlation between the time to read a text and the amplitude of responses to regular words among PW. That is, the slower participants, mainly dyslexics (see Fig. 6), also had lower response amplitudes. Using the same FPVS-EEG approach, a relation to reading performance has been shown in young children: in preschoolers, letter knowledge (accuracy) predicted response amplitudes for letter-strings among pseudofonts on the left occipito-temporal cortex (Lochy et al., 2016). In beginning readers (first and second graders, van de Walle de Ghelcke et al., 2020, 2021), a composite reading score also related to letter-selective response amplitudes. The contrast of letter-strings to pseudofonts in those young children was a rather coarse contrast, as responses may have reflected processes related to gross letter recognition and processing. Here we show that the amplitude of *lexical responses* relates to reading times at the behavioral level. While this result may be particularly salient here due to the large variability of performance in the dyslexic population, it replicates the recent finding of a similar relationship in a population of proficient readers (Marchive et al., 2025). Second, our results highlight that an index of the sublexical route sensitivity (difference of reading times between long and short PW used in behavioral reading tests) correlated positively with response amplitudes for irregular words: the slower participants were in reading long PW vs. short ones, the larger their brain responses to irregular words. We assume that those who are most sensitive to PW length are less efficient in using the sublexical decoding route, and a compensation strategy might be to rely more on lexical mechanisms (see also Sigurdardottir et al., 2021; Kolinski and Tossonian, 2023). Interestingly here, the 2 groups were not distinguished according to this index, and both individuals with dyslexia or typical readers could present low or high sensitivity to PW length.

4.4. Conclusions

This study investigated for the first time the neural responses of adult with dyslexia and typical readers with a FPVS-EEG approach. Neural responses were recorded at the stimulation frequency of deviant stimuli, directly assessing the sensitivity of the visual word recognition system to lexical and orthographic properties. Individuals with dyslexia displayed lower response amplitudes for discrimination of words among pseudowords, and also showed a specific pattern of responses with a lack of discrimination of regular words among pseudowords but discrimination of irregular words. This finding, together with the fact that regularity changes among words induced similar responses in dyslexic and typical readers, suggests a specific characteristic of dyslexia, i.e., that lexical processes are not automatically triggered when the context enhances sublexical processing with pseudowords.

CRediT authorship contribution statement

Aliette Lochy: Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emilie Collette:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Bruno Rossion:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Christine Schiltz:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropsychologia.2025.109137>.

Data availability

Data will be made available on request.

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