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Semantic compensation and novel word learning in university students with dyslexia

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Keywords: students with dyslexia, skilled readers, novel word learning, error rate, reaction  
Times, N200 component, N400 component, sustained frontal negativity, LPC

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## Highlights

- University students with dyslexia are impaired in phonological categorization tasks
- They showed additional evidence of persistent phonological deficits in the novel phonological tasks that were used here
- Phonological deficit does not prevent them from learning the meaning of novel words as well as control skilled readers do
- Students with dyslexia possibly mobilized more frontal resources to reach levels of performance similar to skilled readers when learning novel words
- Overall, results support the semantic compensation hypothesis in adults with dyslexia

## Abstract

The aim of this experiment was to use behavioral and electrophysiological methods to compare university students with dyslexia and matched skilled readers in a novel word learning experiment that included phonological categorization tasks, a word learning phase and a test phase with matching and semantic tasks. Specifically, we aimed at disentangling two hypotheses. If phonological processing drives novel word learning and if phonological processing is impaired in students with dyslexia, they should perform lower than skilled readers not only in the phonological categorization tasks but also in the matching and semantic tasks. By contrast, if students with dyslexia use semantic knowledge to compensate for their phonological deficits, should be able to reach the same level of performance and show similar enhancements of the N200 and N400 components than skilled readers in the matching and semantic tasks. Results at both behavioral and electrophysiological levels showed that the phonological deficits evidenced in the phonological tasks did not impede students with dyslexia to learn the meaning of novel words, possibly because they mobilized more frontal resources than skilled readers. These results are discussed within a general framework of semantic compensation in adults with dyslexia.

## 1. Introduction

Developmental dyslexia (hereafter dyslexia) is a long-lasting reading deficit persisting in adulthood (Cavalli et al., 2018) and which is characterized by poor word decoding, low levels of reading fluency, and poor spelling performance (American Psychiatric Association, 2013). While the issue of whether these deficits are language specific or domain general (e.g., automatization deficit, poor working memory, reduced statistical learning ...) is still hotly debated (Ahissar et al., 2006; Banai & Ahissar, 2010; Jones et al, 2018; Kahta & Schiff, 2019; Nicolson & Fawcett, 1990; Oganian & Ahissar, 2012; Smith-Spark & Fisk, 2007; Vandermosten et al, 2019, but see Schmalz et al, 2017), the causes of dyslexia are likely to be multifactorial (Haft et al., 2016; Perry et al., 2019). Moreover, deficits in phonological processing have long been considered as one of the hallmarks of dyslexia in a majority of children with dyslexia (Ramus, 2003; Saksida et al., 2016; White et al., 2006). The specific nature of this phonological deficit is still under debate (Ramus, 2014; Szenkovits et al., 2016): whether caused by underspecified phonological representations (Boets et al., 2007; Noordenboos et al., 2012), by a delayed access to and retrieval of phonological codes (Boets et al., 2013; Ramus & Szenkovits, 2008) or by less sensitivity to statistical learning (Daikhin et al, 2017; Vandermosten et al, 2019). Whatever the nature of the phonological deficit, one consequence is that it may negatively impact the integration of task demands (Smith-Spark & Fisk, 2007) as well as the acquisition of novel phonological forms and consequently hinder the phonology-to-orthography mapping that is necessary in acquiring reading and writing skills (Ahissar et al., 2006; Kimppa et al., 2018; Thomson & Goswami, 2010). Nevertheless, there is also evidence suggesting that children with dyslexia may compensate for their phonological deficits by relying on morphological and semantic information during reading

1 (Betjemann & Keenan, 2008; Elbro, 1989; Hennessey et al., 2012; Nobre & Salles, 2016;  
2 Quémart & Casalis, 2015). For instance, van der Kleij and collaborators used a picture-word  
3 priming design with 6<sup>th</sup> grade children to test for phonological and semantic priming effects  
4 (van der Kleij, et al., 2019). They found that semantic priming effects, but not phonological  
5 priming effects, were stronger in children with dyslexia than in typical readers. Moreover,  
6 semantic priming effects predicted word and pseudoword reading efficiency in children with  
7 dyslexia, with better reading skills in children showing larger semantic priming effects (for  
8 similar conclusion, see Van Rijthoven et al., 2018).  
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10 Preserved morphological and semantic processing in children may contribute to  
11 explain why some adolescents and young adults with dyslexia, showing persistent  
12 phonological deficits (Elbro et al., 1994; Elbro & Arnbak, 1996; Ramus et al., 2003; Martin et  
13 al., 2010), nevertheless manage to overcome their difficulties to reach a level of reading  
14 comprehension (Deacon et al., 2012; Hebert, et al., 2017), and of general knowledge  
15 sufficiently high to follow up high school and university studies (Elbro et al., 1994). For  
16 instance, it has been suggested that adults with dyslexia possibly involve in conscious  
17 compensation (Nicolson & Fawcett, 1990) to allocate more resources than skilled readers to  
18 semantic information (Robichon et al., 2002). More recently, it has been suggested that  
19 students with dyslexia are able to use semantic cues contained in morphemes (Cavalli et al.,  
20 2016a; 2017a; Law et al., 2015; 2017; Martin et al., 2013) and their enhanced vocabulary  
21 skills (Cavalli et al., 2016b) to compensate for their reading deficits. For instance, using oral  
22 tasks Cavalli et al. (2016a) found preserved morphological processing, together with  
23 impaired phonological processing in students with dyslexia compared to skilled readers  
24 strictly matched on educational level, non-verbal efficiency and vocabulary knowledge. The  
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1 magnitude of the dissociation between phonological and morphological processing was  
2 correlated with reading performance: when the dissociation was strong and in favor of  
3 morphological processing skills, students with dyslexia showed higher reading scores. This  
4 set of results was taken as evidence for a compensation hypothesis based on morphological  
5 skills, possibly because morphemes composing words are short and frequent language units  
6 systematically associated with meaning, thereby facilitating access to word meaning during  
7 reading. In line with this proposal, Cavalli et al. (2017b) recently showed, using both lexical  
8 decision task and magnetoencephalography, that morphological effects were stronger over  
9 frontal regions and developed earlier (100-200 msec) in students with dyslexia than in skilled  
10 readers (around 400 ms). Thus, morphological codes of words are activated earlier in high-  
11 achieving adults with dyslexia than in skilled-readers, suggesting that morphological  
12 processing may play a special role as a compensatory mechanism in this population.  
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### 31 *1.1. The present study*

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35 The aim of the present study was to go one step further in order to better understand  
36 the impact of phonological deficits on higher cognitive functions in university students with  
37 dyslexia. More precisely, we aimed at identifying some of the compensation processes that  
38 these individuals may have developed to overcome their deficits when processing oral  
39 language. In order to do so, we analyzed both behavioral and electrophysiological measures  
40 in a word learning design previously developed by Dittinger et al. (2016; 2017) that allows  
41 exploring different stages of word learning (phonological processing, learning picture-word  
42 associations and testing how well these associations are learned and integrated into  
43 semantic memory). To our knowledge, no electrophysiological studies have yet been  
44 conducted on novel word learning in adults with dyslexia and such studies are needed to  
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1 understand which neural processes are impaired and which are preserved in dyslexia. More  
2 precisely, university students with dyslexia and matched skilled readers were first presented  
3 with phonological categorization tasks in which they categorize novel monosyllabic words  
4 based on pitch (high or low), on vowel duration (short or long), on aspiration (/p/ or /p<sup>h</sup>/ or  
5 on voicing (/b/ or /p/). Participants were then asked to learn the meaning of these novel  
6 monosyllabic words through picture-word associations (learning phase) and they were  
7 subsequently tested on whether they indeed learned the picture-word associations  
8 (matching task) and on whether learning generalized to new related pictures that they had  
9 not seen before in the experiment (semantic task).  
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23           Based on the results described above (e.g., Cavalli et al., 2016a; Martin et al., 2013)  
24 and those by Serniclaes et al. (2004) reporting speech sound discrimination and  
25 categorization deficits in adults with dyslexia (see also the meta-analysis by Noordenbos &  
26 Serniclaes, 2015 for phoneme identification deficits), we predicted that students with  
27 dyslexia should perform lower than skilled readers in the phonological categorization tasks.  
28 Of main interest was to examine the consequences of such phonological difficulties on  
29 subsequent tasks. If phonological processing drives more efficient novel word learning, via  
30 better phonological representation of the novel words and strengthened associations to  
31 word meaning, as predicted by the “phonetic-phonological-lexical continuity” or “cascading”  
32 hypotheses (Cooper & Wang, 2012, 2013; Dittinger et al., 2016, 2017; Wong & Perrachione,  
33 2007), or via enhanced sensitivity to sound regularities (Daikhin et al, 2017; Vandermosten  
34 et al, 2019), phonological deficits in university students with dyslexia should negatively  
35 impact novel word learning. Therefore, dyslexic participants should perform lower than  
36 skilled readers not only in the phonological categorization tasks but also in the matching and  
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1 semantic tasks. By contrast, if students with dyslexia use semantic knowledge  
2 (morphological knowledge is one type of semantic knowledge) to compensate for their  
3 phonological deficits (Cavalli et al., 2016a; 2016b; 2017; Martin et al., 2013), they should  
4 reach the same level of performance than skilled readers in the matching and semantic  
5 tasks.  
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13 Turning to the electrophysiological aspects, novel word learning experiments with  
14 adult skilled readers typically focused on the N400 component, considered as a good index  
15 of semantic processing (Kutas & Hillyard, 1980; 1984). Main results revealed that the N400  
16 component develops very rapidly (e.g., within a few minutes, Dittinger et al., 2016 or with a  
17 single word exposure, Borovsky et al., 2010) when novel words acquire meaning (“fast  
18 mapping, Carey, 1978) and that the N400 to novel words showed a frontal distribution  
19 (Borovsky et al., 2010; Mestres-Missé et al., 2007). This scalp distribution was taken to  
20 reflect the formation of new associations and/or the initial building-up of word  
21 representations in episodic memory (Rodriguez-Fornells, Cunillera, Mestres-Missé, & De  
22 Diego-Balaguer, 2009; Wagner et al., 1998). Interestingly, when the meaning of the novel  
23 words has been integrated into semantic networks (Borovsky et al., 2012; Batterink &  
24 Neville, 2011), the N400 showed the typical centro-parietal distribution (Kutas & Hillyard,  
25 1980).  
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47 Moreover, in the Dittinger et al. (2016) experiment, an N200 component, taken to  
48 reflect early contextual influences (van den Brink et al., 2001) and phonological processing  
49 (Junge et al., 2012; Connolly & Phillips, 1994), also developed together with the N400  
50 component. Because we used the same experimental design as Dittinger et al. (2016), that  
51 aimed at comparing novel word learning in professional musicians and in non-musicians (all  
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1 skilled readers), we expected that results in our group of skilled readers (non-musicians)  
2 would replicate the results of the non-musician skilled readers of Dittinger et al. (2016).  
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4 Thus, based on previous results (Dittinger et al, 2016) we expected an N200 component to  
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6 rapidly develop in the learning phase, with more negative N200 component in the second  
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8 than in the first learning block. We also expected more negative N200 component for  
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10 mismatch than for match words with no difference in N200 amplitude for semantically  
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12 related and unrelated words. Turning to the N400 component, we expected more negative  
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14 N400 over frontal sites in the learning phase and more negative N400 for unexpected words  
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16 than for expected words over parietal sites in the matching task (mismatch vs match words)  
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18 and in the semantic task (related vs unrelated words). Of most interest in the present study,  
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20 was to compare results of skilled readers with results of university students with dyslexia. If  
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22 between-group differences in the phonological categorization tasks influence results in the  
23  
24 subsequent tasks, we expected the N200 and N400 components to be slower to develop  
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26 and/or smaller in amplitude in university students with dyslexia compared to skilled-reader  
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28 participants. By contrast, if adults with dyslexia use semantic compensatory strategies  
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30 (Cavalli et al., 2016a; Martin et al., 2013) to overcome their phonological deficits, we  
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32 expected non-significant between-group differences in the matching and semantic tasks.  
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34 Finally, to fully analyze potential between-group differences in the ERPs, we also measured  
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36 task-related effects on the early sensory components, N100 and P200, as well as on the Late  
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38 Positive Component (LPC) that has been taken to reflect the integration of the meaning of  
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40 newly-learned words into semantic memory (Batterink & Neville, 2011) and/or controlled  
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42 semantic access (Bakker et al., 2015).  
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## 57 2. Method 58 59 60 61 62 63 64 65

## 2.1. Participants

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3 A total of 32 participants, with 16 students with dyslexia and 16 skilled-reader students  
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5 (8 women and 8 men in each group) from Aix-Marseille University took part in the study. All  
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7 were French native speakers with no bilingual participants, they had a normal or corrected  
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9 to normal vision, and had a non-verbal IQ (Raven's Matrices: Raven et al., 1998) within the  
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11 normal range (above the 75<sup>th</sup> percentile). None of them reported neither neurological nor  
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13 psychiatric disorder. All participants with dyslexia were recruited by the "Mission Handicap"  
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15 of Aix-Marseille university and had received a formal diagnosis of dyslexia during primary or  
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17 secondary school. None of the participants were musicians and the number of years involved  
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19 in playing a musical instrument was not significantly different between students with  
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21 dyslexia and skilled readers.  
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30 As reported in Table 1, the two groups were matched on chronological age (mean:  
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32 21.2 years old), educational level (mean: 2 years of higher education), vocabulary knowledge  
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34 (the EVIP scale, Dunn et al., 1993), and non-verbal IQ. They were also matched on field of  
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36 study (humanities and social science, psychology, biology, neuroscience, and mathematics).  
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41 Reading efficiency was assessed with a French reading test standardized for adults  
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43 (*l'Alouette*, Cavalli et al., 2018), taking both accuracy and speed into account. Efficiency of  
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45 the lexical and non-lexical reading routes (Pritchard et al., 2012) were assessed using  
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47 respectively a one-minute word reading aloud test and a two-minute pseudo-word reading  
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49 aloud test. The first test was composed of 120 words varying in length (from 4 to 7 letters)  
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51 and frequency (from the French database [lexique.org](http://lexique.org)). The time limit to read these words  
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53 was one minute. The second test was composed of 116 pseudowords words varying in  
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number of syllables (one or two) and length (from 5 to 7 letters). The time limit to read these pseudo-words was two minutes.

Phonological skills involved in reading were assessed through EVALEC's initial phoneme deletion task (Sprenger-Charolles, Colé, Béchenec, & Kipffer-Piquard, 2005). The two groups differed significantly in reading and phonological skills (Table 1).

Written consent was obtained before starting the experiment. The study received a prior approval from the Ethics Committee of Aix-Marseille University. Participants received a monetary compensation at the end of the experiment.

**Table 1.** Cognitive profile of readers with and without dyslexia. Efficiency scores were obtained by dividing accuracy scores with the averaged speed for each participant. T-values were obtained from paired student t-tests comparing the two groups of participants.

	Students with dyslexia (n=16)		Skilled readers (n=16)		t values	
	Mean	SD	Mean	SD	t(30)	p
Chronological age	21.4	2.22	21	1.61	0.61	0.54
Year of higher Education	1.94	0.93	2.06	0.93	0.38	0.71
Nonverbal IQ (Raven Matrices, max=58)	46.31	5.59	48.88	5.51	1.31	0.20
Musical training experience	2.37	3.28	3.12	4.54	0.53	0.59
Vocabulary (EVIP, max=51)	39.5	4.70	40	4.97	0.29	0.77
Reading efficiency score (Alouette)	347.77	94.28	502.36	103.21	4.42	0.0001
Word Reading (efficiency)	81.22	23.49	110.58	20.35	3.78	0.001
Pseudo-Word Reading (efficiency)	82.51	44.16	141.39	42.99	3.82	0.001
Phonological Awareness						
Accuracy	25.63	3.48	27.94	2.17	2.25	0.03
Response Time (msec)	2048.24	500.5	1547.94	368.63	3.22	0.003

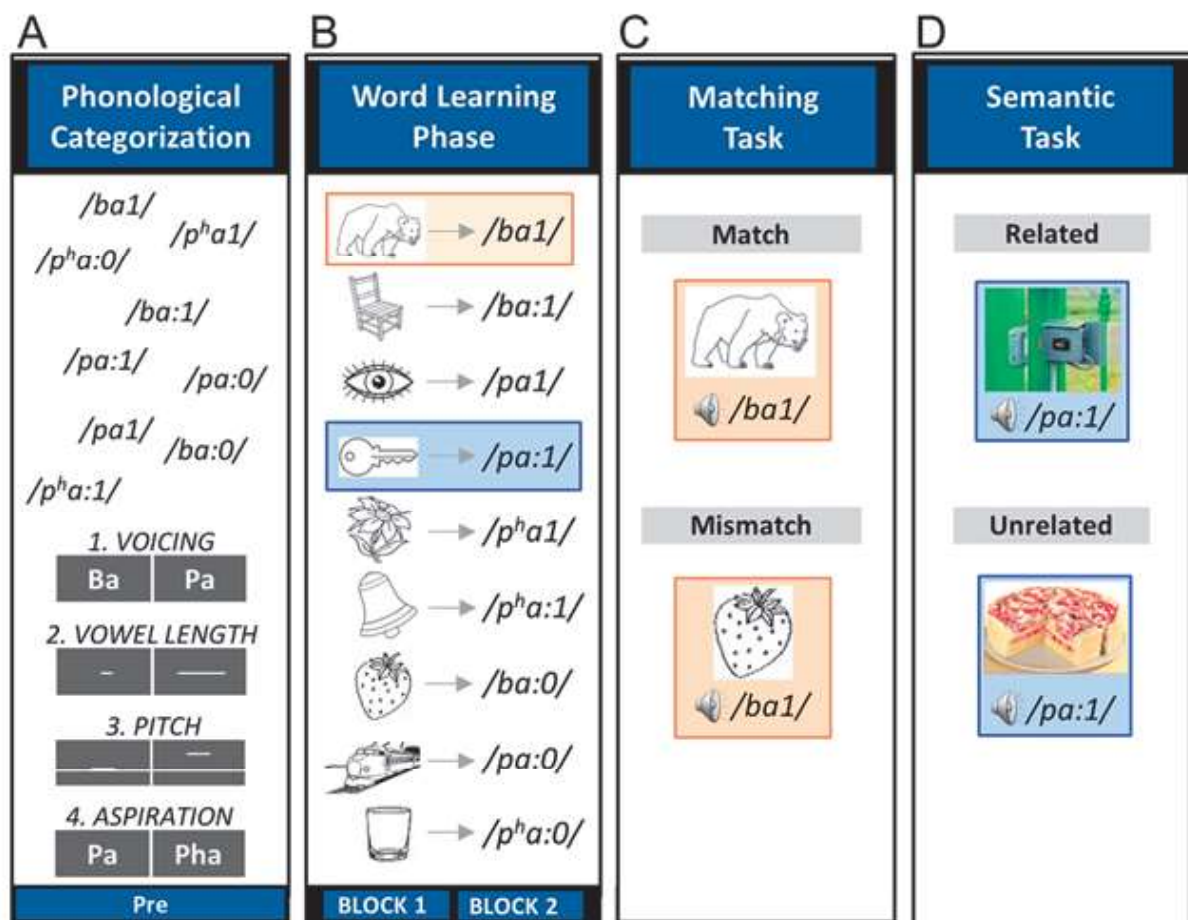
## 2.2. Materials

1 We used the nine Thai monosyllabic words (/ba1/, /pa1/, /p<sup>h</sup>a1/, /ba:1/, /pa:1/,  
2 /p<sup>h</sup>a:1/, /ba:0/, /pa:0/, /p<sup>h</sup>a:0/) that were recorded by a Thai-French bilingual woman for the  
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4 Dittinger et al. (2016) experiment. The vowels varied in duration, with short (261 msec on  
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6 average) and long vowels (531 msec in average), and in fundamental frequency, with low-  
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8 tone (F0 = 175 Hz on average) and high-tone (218 Hz on average). Moreover, consonants  
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10 varied in Voice Onset Time (VOT; /b/ = -144 msec vs. /p/, VOT = 3 msec vs. /p<sup>h</sup>/,  
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12 VOT=77msec). Each word was recorded five times to reproduce the typical variability  
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14 encountered in natural languages.  
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21 For the visual stimuli, we used the same pictures as in Dittinger et al. (2016). For the  
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23 learning phase, we presented nine black and white line drawings of familiar objects with  
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25 monosyllabic French names (i.e. ours/bear, fleur/flower, clé/key, chaise/chair, cloche/bell,  
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27 oeil/eye, fraise/strawberry, train/train, verre/glass), that were controlled for name  
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29 agreement, image agreement, familiarity, image complexity, age of acquisition, and  
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31 frequency, based on the French normative measures for the Snodgrass & Vanderwart  
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33 pictures (Alario and Ferrand, 1999). These same nine pictures were then presented in the  
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35 matching task. For the semantic task, 60 new pictures were selected from the internet that  
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37 were paired on each trial with one of the nine pictures presented in the learning phase and  
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39 in the matching task. These new pictures were pretested with students from Aix-Marseille  
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41 University (n = 60; age range = 19-25 years) who were asked to rate the semantic  
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43 relatedness between new and “old” pictures (i.e., from the learning phase and matching  
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45 task) on a scale from 1 to 5, with 1 being not related at all and 5 being very well related. Only  
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47 picture pairs that were on average rated higher than 4 in related conditions and lower than 2  
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49 in unrelated conditions were accepted for the experiments (i.e., 54 new pictures out of 60).  
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### 2.3. Procedure

The experimental session included four phonological categorization tasks, presented at the beginning of the session, the learning phase, the matching task and the semantic task (see Figure 1). These different tasks were performed successively with a few minutes in between for the participants to rest and to explain them the instructions for each new task. Participants were seated in a Faraday cage, at about one meter from a computer screen. Auditory stimuli were presented binaurally, through headphones. Responses were recorded using two response buttons placed in each hand of the participants. Visual and Auditory stimuli presentation were controlled by the Presentation Software (Version 18.1, Neurobehavioral Systems, Berkeley).



1 **Figure 1.** Experimental design. A. Phonological categorization task, participants had to  
2 categorize nine natural Thai monosyllabic words based on voicing, vowel duration, pitch or  
3 aspiration contrasts. B. Word learning phase: participants learned the meaning of the novel  
4 words through picture-word associations. C. Matching task: words were presented with a  
5 picture that matched or mismatched the previously learned association. D. Semantic task:  
6 words were presented with novel pictures that were semantically related or unrelated to the  
7 word.  
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### 10 *2.3.1. Phonological categorization tasks*

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12 Participants performed four phonological categorization tasks that lasted for 2-3  
13 minutes each and that were performed at the beginning of the session. All nine monosyllabic  
14 words were presented ten times in each task, in a pseudorandomized order. Participants had  
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16 to categorize words according to the voicing contrast (i.e. /b. or /p/), to the aspiration  
17 contrast (i.e. /p/ or /ph/), to the duration of the vowel (i.e. short or long) and to the pitch of  
18 the vowel (i.e. low or high). Participants were told to respond as fast and accurately as  
19 possible. The phonological contrast and the side of response were illustrated on the screen.  
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21 The side of response and order of the tasks were counterbalanced between participants.  
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### 33 *2.3.2. Word learning phase*

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35 Participants had to learn the meaning of the nine words through picture-word  
36 associations. In each trial, a picture was presented on the screen, followed by the auditory  
37 word after 810 msec. Trials lasted 2000 msec. Each picture-word associations were  
38 presented 20 times, in two blocks and in pseudo-randomized order. Two lists were created  
39 so that participants learned different picture-word associations. No behavioral response was  
40 required, but participants knew that they would be evaluated in the following tasks.  
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### 53 *2.3.3. Matching task*

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In each trial, participants had to decide whether the association formed by a picture followed 810 msec after by a word, did or did not match the picture-word associations previously learned in the word learning phase. They were asked to press the corresponding button as fast and accurately as possible. At the end of the trial, a row of XXX appeared on the screen for 1000 msec during which participants were asked to blink to minimize eye movement artefacts during the recording periods of interest. Trials lasted 3750 msec. Participants performed four familiarization trials to ensure that they understood the task. Each word was presented 20 times, half in the match and half in the mismatch condition. The total of 180 picture-word associations was pseudo-randomly presented within two blocks.

#### 2.3.4. *Semantic task*

In each trial, participants had to decide whether the association formed by one of the new pictures followed 1560 msec after by a previously learned word, was semantically related or unrelated by pressing the corresponding button as fast and accurately as possible. At the end of the trial, a row of XXX appeared on the screen for 1000 msec during which participants were asked to blink to minimize eye movement artefacts during the recording periods of interest. Trials lasted 4500 msec. Participants performed four familiarization trials to ensure they understood the task. Each word was presented 12 times, half in semantically related and half in semantically unrelated condition. The total of 108 trials was pseudo-randomly presented within two blocks.

#### 2.4. *EEG acquisition and preprocessing*

1 Continuous EEG was recorded at a sampling rate of 512 Hz with a band-pass filter of 0-  
2 102 Hz by using a Biosemi amplifier system (BioSemi Active 2, Amsterdam, The Netherland)  
3  
4 with 32 active Ag/Cl electrodes (Biosemi Pintype) located at standard positions according to  
5  
6 the International 10/20 system (Jasper, 1958). Electrode impedance was kept under 5 k $\Omega$ .  
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8 The EOG was recorded from flat-type active electrodes placed 1 cm away from the two  
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10 external canthi and beneath the right eye. Two additional electrodes were placed on the  
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12 right and left mastoids. EEG data were analyzed using Brain Vision Analyzer software  
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14 (Version 1.05; Brain Products, Munchen, Germany). Data were re-referenced offline to the  
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16 average of left and right mastoid and filtered with a bandpass filter from 0.1 to 30Hz (slope  
17  
18 of 24 dB/oct). Components associated with eye movement were identified and removed  
19  
20 using Independent Component Analysis (ICA) and inverse ICA (EEGLab, Delorme & Makeig,  
21  
22 2004). Baseline correction, DC-detrend and removal of artefacts above a gradient criterion of  
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24 10  $\mu$ V/msec or a max–min criterion of 100  $\mu$ V were applied automatically. In all tasks, ERPs  
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26 were time-locked to word onset and segmented into 1200 msec epochs in the phonological  
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28 categorization tasks, 1400 msec in the learning phase and 1700 msec in the matching and  
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30 semantic tasks, including a 200 msec baseline. Individual averages were computed for each  
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32 condition, and then averaged across all participants.  
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44 Statistical analyses were conducted using the Statistica Software (Version 12.0;  
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46 StatSoft, inc. Tulsa, OK). In the phonological tasks, behavioral data (percentage of errors and  
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48 response times) were analyzed using two-ways ANOVA with Group (students with dyslexia vs  
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50 skilled readers) as a between-subject factor and Tasks (Voicing vs aspiration vs Duration vs  
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52 Pitch) as a within-subject factor. In the matching and semantic tasks, data were analyzed  
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54 using two-ways ANOVAs with Group (students with dyslexia vs skilled readers) as a between-  
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1 subjects factor and Condition (Match vs Mismatch) or Condition (related vs unrelated), as a  
2 within-subject factor.  
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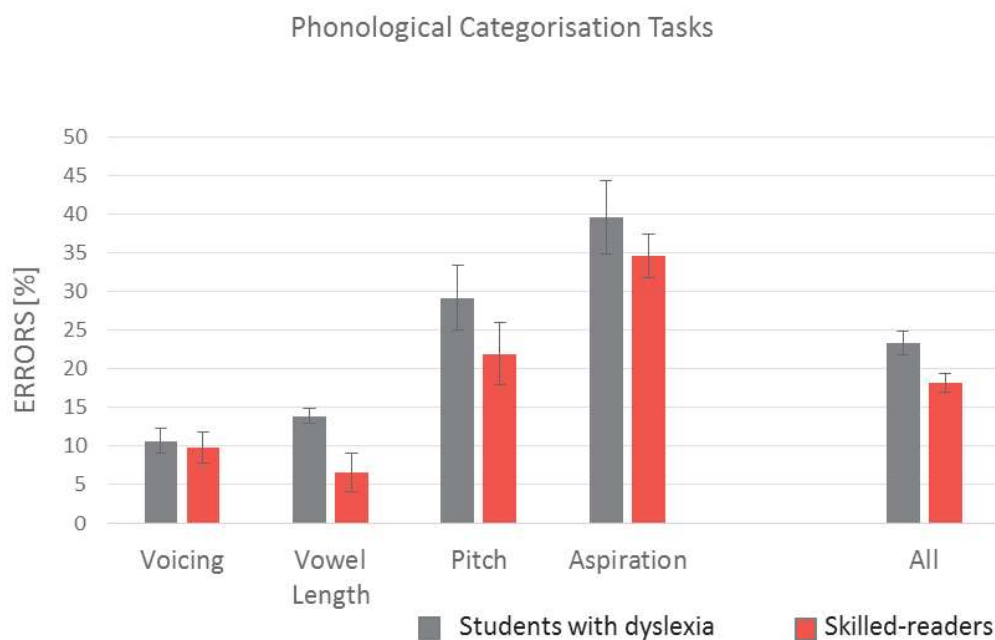
4  
5 In the matching and semantic tasks, ERPs were analyzed for correct responses only. In  
6 all experiments, ERPs analysis included 9 electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz and P4) and  
7 mean amplitudes were computed in different time windows according to the components of  
8 main interest: N100 (40-140 msec.), P200 (140-240 msec.), N200 (240-340 msec.), N400  
9 (340-540 msec.) and LPC (540-740 msec.). For each experiment, electrophysiological data  
10 were analyzed using four-ways ANOVAs including Group (students with dyslexia vs skilled  
11 readers) as a between-subject factor and Block (1 vs 2) in the word learning phase, Condition  
12 (Match vs Mismatch) in the matching task or Condition (Related vs Unrelated) in the  
13 semantic task, together with Laterality (Left vs Midline vs Right) and Anterior/Posterior  
14 positions (Frontal vs Central vs Parietal) as within-subject factors on the mean amplitude of  
15 the ERP components of main interest. Finally, to compare the mean amplitude of the N400  
16 component between experiments, five-ways ANOVA were conducted with Group (students  
17 with dyslexia vs skilled readers) as a between-subject factor and Task (Learning phase vs  
18 Matching vs Semantic), Condition (Block 1 vs Block 2 or Match vs Mismatch or Related vs  
19 Unrelated), Laterality (Left vs Midline vs Right) and Anterior/Posterior positions (Frontal vs  
20 Central vs Parietal) as within-subject factors.  
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### 46 3. Results

#### 47 3.1. Phonological Categorization Tasks:

##### 48 3.1.1. Behavioral data.

1 Students with dyslexia made overall more errors (23.33%, SE = 1.22) than skilled  
 2 readers (18.24%, SE = 1.50; main effect of Group:  $F(1,30) = 6.91$ ,  $p = .01$ ; effect size:  $\eta^2 =$   
 3  
 4 0.19; see Figure 2). In addition, all participants made significantly more errors in the  
 5 Aspiration (37.08%, SE = 2.72) and Pitch Tasks (25.26%, SE = 2.94) than in the Voicing  
 6  
 7 (10.28%, SE = 2.94) and duration Tasks (10.24%, SE = 1.48; Tukey test for each of the four  
 8  
 9 comparisons:  $p < .001$ ; main effect of Tasks:  $F(1,30) = 32.5$ ,  $p < .001$ ; effect size:  $\eta^2 = 0.52$ ).  
 10  
 11 The Group by Task interaction was not significant ( $F < 1$ ). Response times were not analyzed  
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 13 in the phonological tasks because they were confounded by intrinsic differences in stimulus  
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 15 features (e.g., syllables are longer in the duration task than in the pitch task).  
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**Figure 2.** Percentage of errors for students with dyslexia (in grey) and for skilled readers (in red), in the four phonological categorization tasks (left) and averaged across tasks (right).

### 3.2. Word Learning Phase

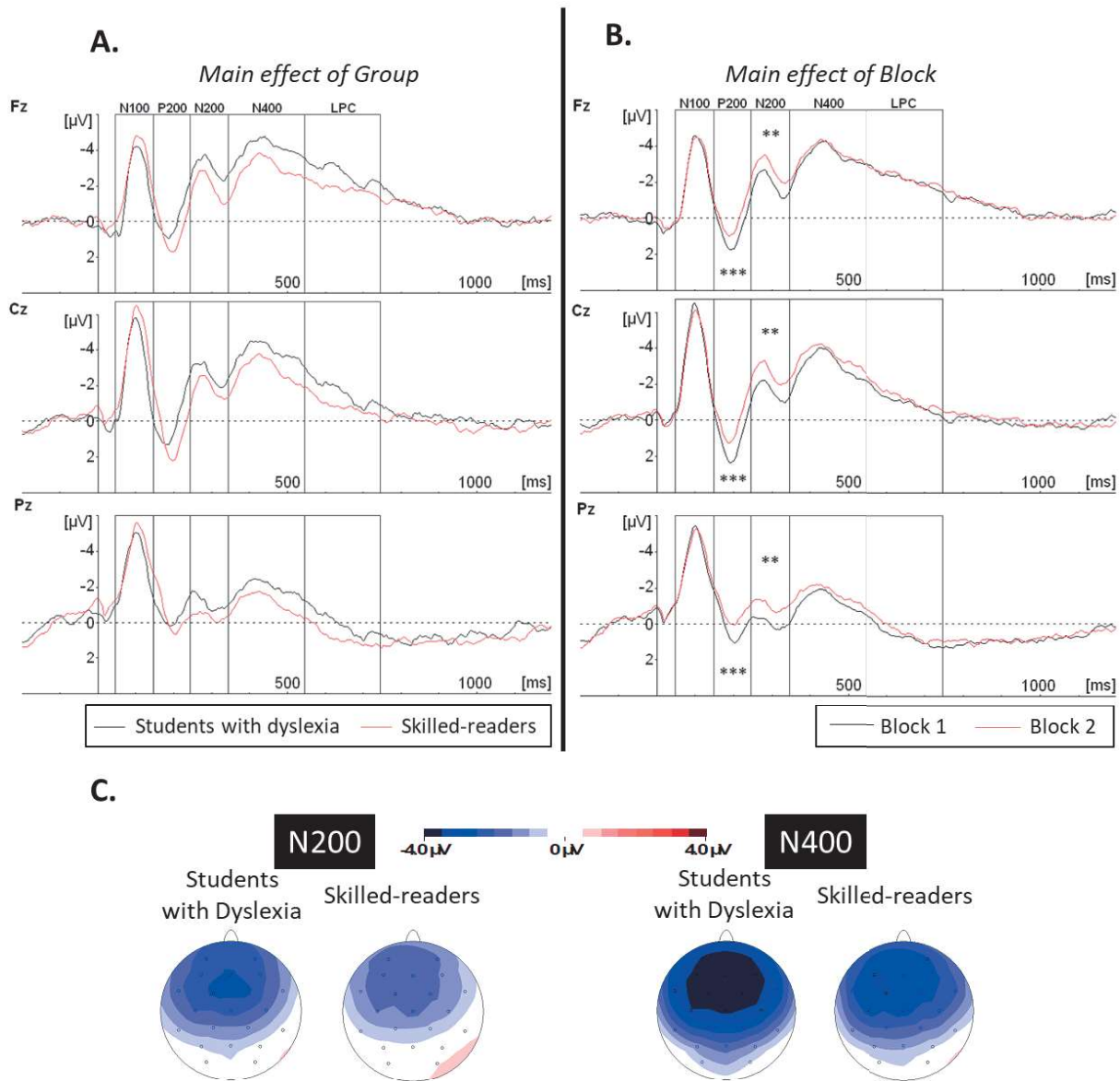
#### 3.2.1. Electrophysiological data.

1 For the N100 component, neither the main effects of Group ( $F < 1$ ) and Block ( $F < 1$ )  
2 nor any interaction including these two factors were significant (see Figures 3A and 3B). For  
3 the P200 component, results showed no main effect of Group ( $F < 1$ ) but the P200 was  
4 significantly more positive in block 1 (0.18  $\mu\text{V}$ , SE = 0.31) than in block 2 (-0.49  $\mu\text{V}$ , SE = 0.36;  
5 main effect of Block:  $F(1,30) = 23.21$ ,  $p < .001$ ; effect size:  $\eta^2 = 0.42$ ; see Figures 3A and 3B).  
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13 For the N200 component, the main effect of Group was not significant ( $F < 1$ ) but the  
14 amplitude of the N200 increased from Block 1 (-0.93  $\mu\text{V}$ , SE = 0.33) to Block 2 (-1.77  $\mu\text{V}$ , SE =  
15 0.36; main effect of Block:  $F(1,30) = 10.18$ ,  $p = .003$ ; effect size:  $\eta^2 = 0.25$ ; see Figures 3A  
16 and 3B). Moreover, the N200 was more negative over frontal (-2.05  $\mu\text{V}$ , SE = 0.42) and  
17 central sites (-1.71  $\mu\text{V}$ , SE = 0.36) compared to parietal sites (-0.31  $\mu\text{V}$ , SE = 0.24; Tukey tests:  
18 frontal vs parietal and central vs parietal,  $p < .001$ ; main effect of Anterior/Posterior  
19 positions:  $F(2,60) = 37.78$ ,  $p < .001$ ; effect size:  $\eta^2 = 0.56$ ; see Figure 3C). The interactions  
20 including the Group or Block factors were not significant.  
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34 For the N400 component, the main effects of Group ( $F(1,30) = 2.06$ ,  $p = .16$ ) and  
35 Block ( $F < 1$ ) were not significant, but the amplitude of the N400 component was more  
36 negative over frontal (-3.28  $\mu\text{V}$ , SE = 0.32) and central sites (-2.92  $\mu\text{V}$ , SE = 0.29) compared to  
37 parietal sites (-1.08  $\mu\text{V}$ , SE = 0.29; Tukey tests: frontal vs parietal and central vs parietal,  $p <$   
38 .001; main effect of Anterior/Posterior positions:  $F(2,60) = 75.28$ ,  $p < .001$ ; effect size:  $\eta^2 =$   
39 0.71; see Figures 3A, 3B and 3C). There was no significant interaction including the Group or  
40 Blocks factors.  
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53 For the LPC, neither the main effects of Group ( $F(1,30) = 2.64$ ,  $p = .11$ ) and Block ( $F <$   
54 1) nor any significant interaction including these two factors were significant.  
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**Figure 3.** Word Learning Phase. A. Grand averages across the two blocks are overlapped for students with dyslexia (black line) and skilled readers (red line). B. Grand averages across participants (students with dyslexia and skilled readers) are overlapped for block 1 (black line) and block 2 (red line). ERPs are illustrated for the midline at frontal (Fz), central (Cz) and parietal (Pz) sites. C. Topographic voltage distribution maps in the N200 (left) and N400 (right) latency bands (230-340 ms and 340-550 ms, respectively) are represented for students with dyslexia and for skilled readers. Voltage values are scaled from -4.0 to +4.0  $\mu$ V.

### 3.3. Matching Task

#### 3.3.1. Behavioral data.

Students with dyslexia made more errors and were slower than skilled readers (Errors: students with dyslexia = 29.13% (SE = 2.09) and skilled readers = 22.05% (SE = 2.58); main effect of Group:  $F(1,30) = 4.55$ ,  $p = .04$ ; effect size:  $\eta^2 = 0.13$ , and response time: student with dyslexia = 1149 msec (SE = 47) and skilled readers = 1009 msec (SE = 43); main effect of Group:  $F(1,30) = 4.75$ ,  $p = .04$ ; effect size:  $\eta^2 = 0.14$ ), with no significant differences between Match and Mismatch words (main effect of Condition, errors:  $F(1,30) = 1.84$ ,  $p = .18$  and response time:  $F < 1$ ) and no Group by Condition interaction (errors and response time:  $F < 1$ ; see Table 2).

**Table 2.** Percentage of errors and response time in the matching and the semantic tasks for

	Matching Task		Semantic Task	
	Match	Mismatch	Related	Unrelated
Students with dyslexia				
Errors (%)	26.53 (10.83)	31.74 (11.5)	41.48 (12.9)	30.21 (13.38)
Response Time (msec)	1141 (198)	1157 (192)	1264 (237)	1354 (207)
Skilled readers				
Errors (%)	21.11 (14.08)	22.99 (11.04)	36.34 (14.34)	23.61 (10.42)
Response Time (msec)	1003 (191)	1016 (161)	1167 (217)	1259 (227)

readers with and without dyslexia. Standard deviations are reported in parentheses.

#### 3.3.2. Electrophysiological data

1 For the N100 component, neither the main effects of Group ( $F < 1$ ) and Condition ( $F <$   
2 1) nor any interactions including these two factors were significant (see Figures 4A and 4B).  
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4 For the P200 component, the main effect of Group was not significant ( $F < 1$ ) but the P200  
5 was more positive for Match words ( $-0.37 \mu\text{V}$ ,  $\text{SE} = 0.42$ ) compared to mismatch words ( $-0.81$   
6  $\mu\text{V}$ ,  $\text{SE} = 0.41$ ; main effect of Condition:  $F(1,30) = 7.93$ ,  $p = .008$ ; effect size:  $\eta^2 = 0.20$  ; see  
7 Figures 4A and 4B). There was no significant interaction including the Group or Condition  
8 factor.  
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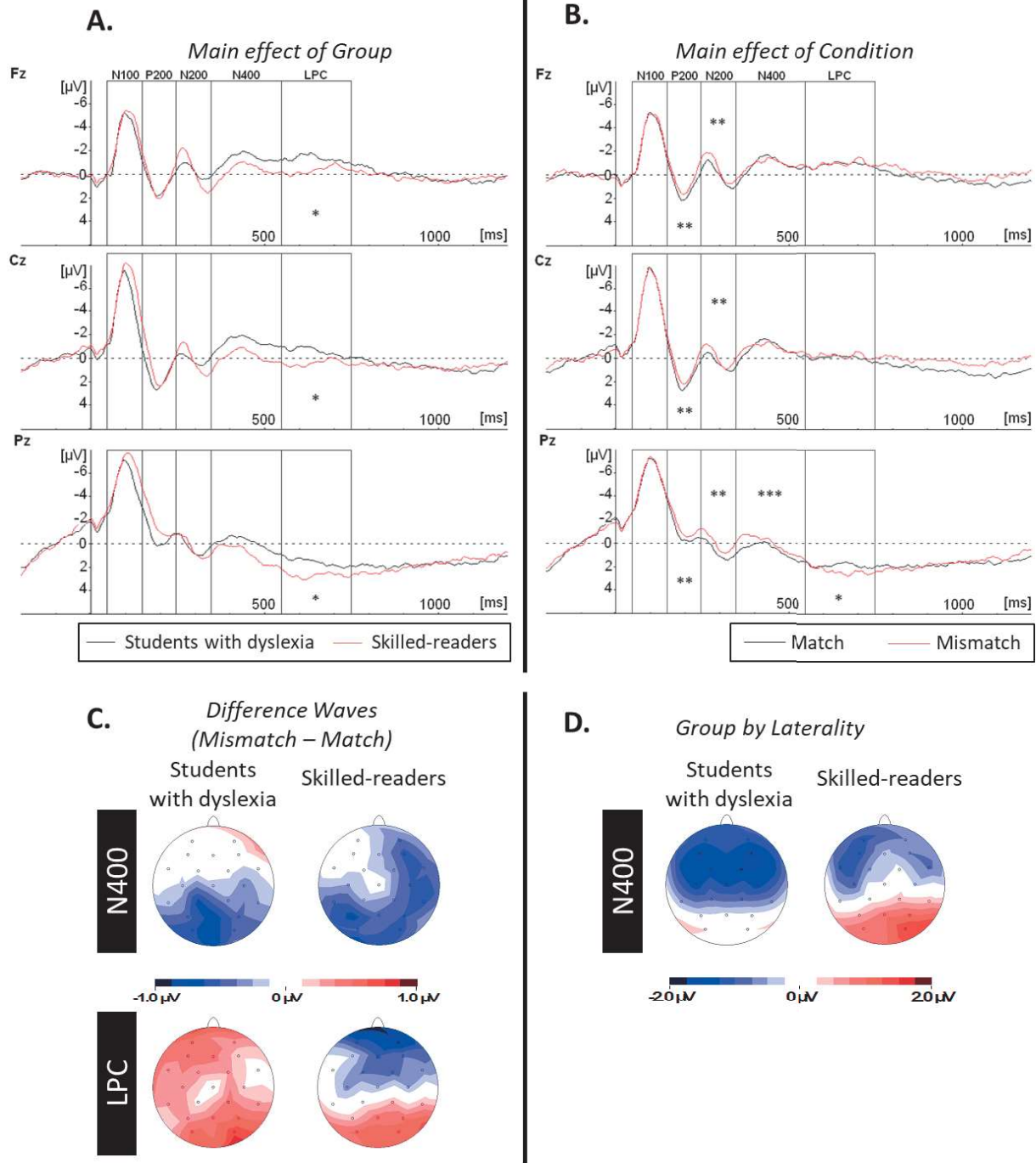
10 For the N200 component, the main effect of Group was not significant ( $F < 1$ ) but,  
11 over scalp sites, the N200 was more negative to Mismatch words ( $-0.47 \mu\text{V}$ ,  $\text{SE} = 0.48$ )  
12 compared to Match words ( $0.15 \mu\text{V}$ ,  $\text{SE} = 0.48$ ; main effect of Condition:  $F(1,30) = 9.87$ ,  $p =$   
13  $.004$ ; effect size:  $\eta^2 = 0.24$ ; see Figures 4A and 4B). There was no significant interaction  
14 including the Group or Condition factors.  
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16 For the N400 component, the main effects of Group ( $F(1,30) = 1.53$ ,  $p = .23$ ) and  
17 Condition ( $F(1-30) = 1.37$ ,  $p = .25$ ) were not significant. However, the Condition by  
18 Anterior/Posterior interaction was significant ( $F(2,60) = 3.59$ ,  $p = .03$  ; effect size :  $\eta^2 = 0.11$ ),  
19 showing that over parietal sites only, the N400 component was more negative for Mismatch  
20 words ( $0.04 \mu\text{V}$ ,  $\text{SE} = 0.41$ ) than for Match words ( $0.58 \mu\text{V}$ ,  $\text{SE} = 0.36$ ; Tukey test over Frontal:  
21  $p = .95$ ; Central:  $p = .39$  and Parietal:  $p < .001$ ; see Figures 4A and 4B). The N400 effect  
22 (Mismatch – Match) is illustrated on Figure 4C. Moreover, the Group by Laterality ( $F(2,60) =$   
23  $3.19$ ,  $p = .05$  ; effect size:  $\eta^2 = 0.08$ ) interaction was significant. For skilled readers, the N400  
24 component was more negative over Left ( $-0.55 \mu\text{V}$ ,  $\text{SE} = 0.39$ ) compared to Midline ( $0.08 \mu\text{V}$ ,  
25  $\text{SE} = 0.40$ ; Tukey test:  $p = .001$ ) and Right sites ( $-0.06 \mu\text{V}$ ,  $\text{SE} = 0.35$ ; Tukey test:  $p = .02$ ) with  
26 no significant hemispheric differences for students with dyslexia (Left:  $-1.02 \mu\text{V}$ ,  $\text{SE} = 0.51$ ;  
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Midline: 0.87  $\mu\text{V}$ , SE = 0.59 and Right sites: -0.98  $\mu\text{V}$ , SE = 0.46, Tukey tests always > .90, see Figure 4D).

For the LPC, the main effect of Group was significant with less positive LPC for students with dyslexia (-0.23  $\mu\text{V}$ , SE = 0.40) than for skilled readers (0.83  $\mu\text{V}$ , SE = 0.26;  $F(1,30) = 4.81$ ,  $p = .04$ ; effect size:  $\eta^2 = 0.14$ ; see Figure 4A). The main effect of Condition was not significant ( $F < 1$ ), but the Condition by Anterior-Posterior interaction was significant ( $F(2,60) = 3.73$ ,  $p = .03$ ; effect size:  $\eta^2 = 0.11$ ) with more positive LPC to Mismatch (2.15  $\mu\text{V}$ , SE = 0.35) than to Match words (1.75  $\mu\text{V}$ , SE = 0.34) over Parietal sites (Tukey tests: Frontal:  $p = 1$ , Central:  $p = .99$  and Parietal:  $p = .04$ ; see Figure 4B). The LPC effect (Mismatch – Match) is illustrated on Figure 4C.



**Figure 4.** Matching Task. A. Grand averages across conditions (Match and Mismatch words) are overlapped for students with dyslexia (black line) and skilled readers (red line). B. Grand averages across participants (students with dyslexia and skilled readers) are overlapped for match (black line) and mismatch (red line) words. ERPs are illustrated for the midline at frontal (Fz), central (Cz) and parietal (Pz) sites. C. Topographic voltage distributions maps (from the differences waves: Mismatch - Match) of the N400 component and LPC are represented for students with dyslexia and skilled readers. Voltage values are scaled from -1.0 to +1.0  $\mu\text{V}$ . D. Topographic voltage distribution maps of the N400 component are represented for students with dyslexia and skilled readers. Voltage values are scaled from -2.0 to +2.0  $\mu\text{V}$ .



### 3.4. Semantic Task

#### 3.4.1. Behavioral data.

Results showed no significant between-group differences either on errors or on response time (main effect of Group, errors:  $F(1,30) = 3.35$ ,  $p = .08$  and response time:  $F(1,30) = 1.61$ ,  $p = .21$ ) but participants made more errors and were faster for semantically related (errors: 38.77% (SE = 1.68) and response time: 1215 msec. (SE = 28)) than unrelated words (main effect of Condition, errors: 26.91% (SE = 1.53),  $F(1,30) = 13.39$ ,  $p < .001$ , effect size:  $\eta^2 = 0.31$ , and response time: 1306 msec. (SE = 27),  $F(1,30) = 18.54$ ,  $p < .001$ , effect size:  $\eta^2 = 0.38$ ). The Group by Condition interaction was not significant either on errors or on response time ( $F < 1$  in both cases; see Table 2).

#### 3.4.2. Electrophysiological data.

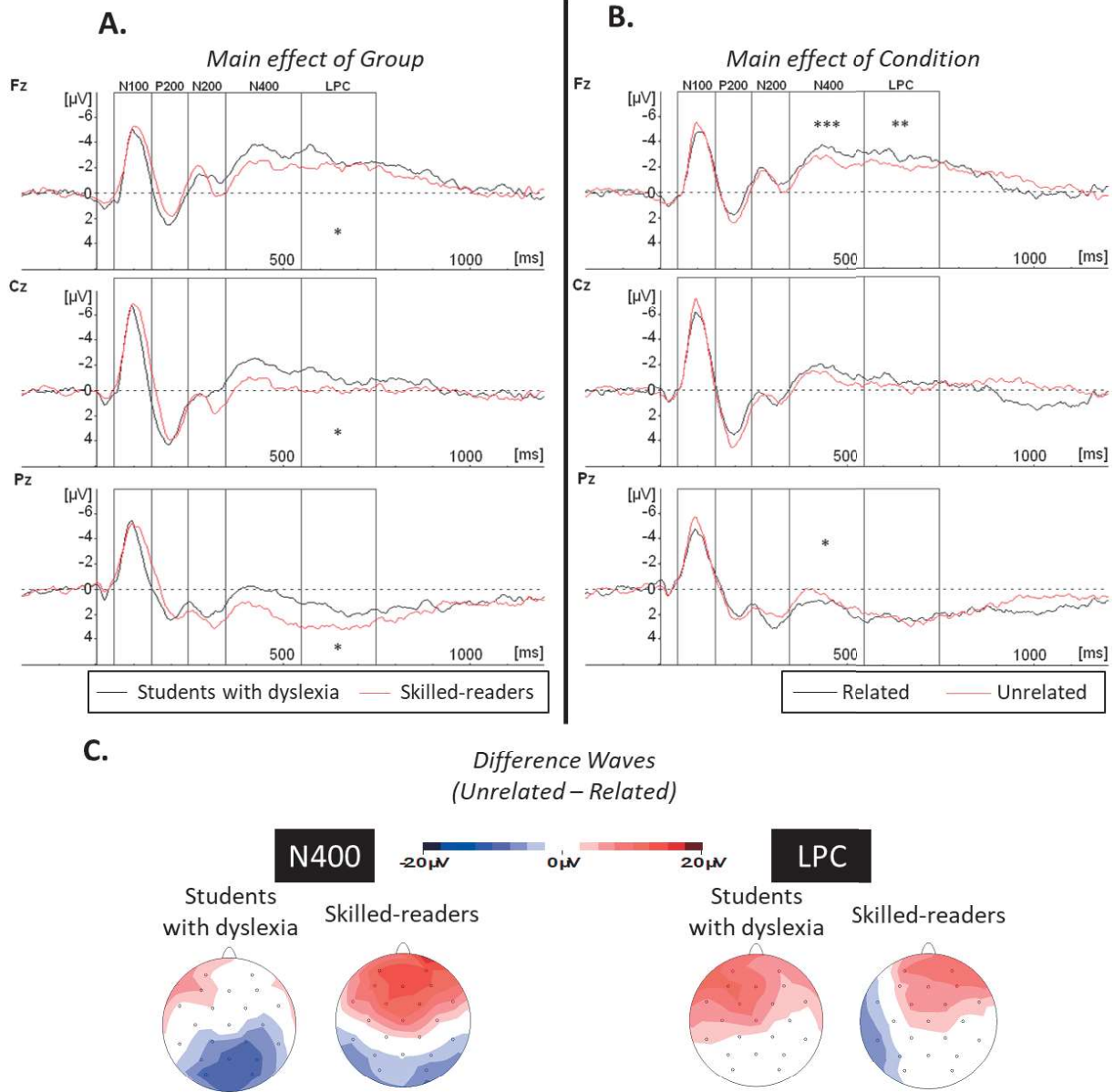
For the N100 component, the main effects of Group ( $F < 1$ ) and Condition ( $F(1,30) = 1.18$ ,  $p = .28$ ) were not significant (see Figures 5A and 5B). For the P200 component, neither the main effects of Group ( $F(1,30) = 1.27$ ,  $p = .27$ ) and Condition ( $F(1,30) = 3.65$ ,  $p = .06$ ), nor the interactions including these two factors were significant (see Figures 5A and 5B).

For the N200 component, the main effects of Group ( $F < 1$ ) and Condition ( $F < 1$ ) were not significant (see Figures 5A and 5B). The Condition by Anterior/Posterior interaction was significant ( $F(2,60) = 3.91$ ,  $p = .02$ ) but Tukey tests did not reveal any significant differences (see Figure 5B). There was no other significant interaction including Group or Condition.

For the N400 component, neither the main effects of Group ( $F(1,30) = 2.44$ ,  $p = .13$ ) and Condition ( $F < 1$ ), nor the Group by Condition interaction ( $F(1,30) = 1.04$ ,  $p = .32$ ) were

1 significant. However, the Condition by Anterior/Posterior interaction was significant ( $F(2,60)$   
2 = 13.12,  $p < .001$ ; effect size:  $\eta^2 = 0.30$ ), showing that over parietal sites (Tukey test:  $p = .04$ ),  
3  
4 the N400 was more negative for Unrelated words ( $-0.65 \mu\text{V}$ ,  $\text{SE} = 0.34$ ) than for Related  
5  
6 words ( $1.20 \mu\text{V}$ ,  $\text{SE} = 0.32$ ). By contrast, over frontal sites (Tukey tests, Frontal:  $p = .001$ ;  
7  
8 Central:  $p = .18$ ), the N400 was more negative for Related words ( $-2.92 \mu\text{V}$ ,  $\text{SE} = 0.45$ ) than  
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10 for Unrelated words ( $-2.17 \mu\text{V}$ ,  $\text{SE} = 0.37$ ; see Figures 5A and 5B). The N400 effect (Unrelated  
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12 – Related) is illustrated on Figure 5C.  
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18 For the LPC, the main effect of group was significant with less positive LPC for  
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20 students with dyslexia ( $-0.87 \mu\text{V}$ ,  $\text{SE} = 0.34$ ) than for skilled readers ( $0.17 \mu\text{V}$ ,  $\text{SE} = 0.31$ ;  
21  
22  $F(1,30) = 4.27$ ,  $p = .05$ , effect size:  $\eta^2 = 0.12$ ). The main effect of Condition was not significant  
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24 ( $F < 1$ ; see Figures 5A and 5B). However, the sustained negativity that developed over Frontal  
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26 sites in the same latency band was more negative to related words ( $-2.81 \mu\text{V}$ ,  $\text{SE} = 0.41$ ) than  
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28 to unrelated words ( $-2.10 \mu\text{V}$ ,  $\text{SE} = 0.31$ ; Tukey tests, Frontal:  $p = .01$ ; Central:  $p = .70$ ; and  
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30 Parietal:  $p = .99$ ; Condition by Anterior/Posterior interaction:  $F(2,60) = 3.47$ ,  $p = .04$ ; effect  
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32 size:  $\eta^2 = 0.10$ ; see Figure 5B). The LPC effect (Unrelated – Related) is illustrated on Figure  
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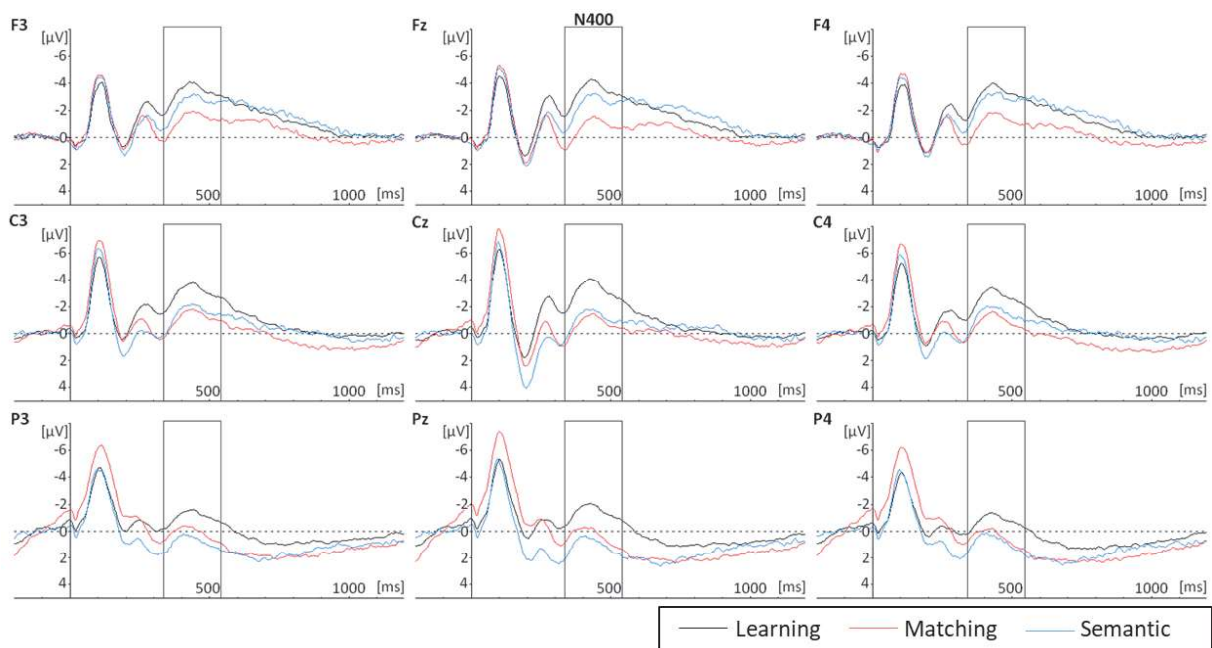


**Figure 5.** Semantic Task. A. Grand averages across conditions (semantically related and unrelated words) are overlapped for students with dyslexia (black line) and skilled readers (red line). B, Grand averages across participants (students with dyslexia and skilled readers) are overlapped for match (black line) and mismatch (red line) words. ERPs are illustrated for the midline at frontal (Fz), central (Cz) and parietal (Pz) sites. C. Topographic voltage distributions maps (from the differences waves: Unrelated – Related) of the N400 component and LPC are represented for students with dyslexia and skilled readers. Voltage values are scaled from -2.0 to +2.0  $\mu$ V.

### 3.5. Between-tasks comparison

### 3.5.1. Electrophysiological data.

Results showed no main effect of Group ( $F(1,30) = 2.56, p < .12$ ) but a significant main effect of Task ( $F(2,60) = 32.03, p < .001$ ; effect size:  $\eta^2 = 0.51$ ) with more negative sustained negativity in the word learning phase ( $-2.43 \mu\text{V}, \text{SE} = 0.26$ ) than in the semantic ( $-0.99 \mu\text{V}, \text{SE} = .031$ ) and matching tasks ( $-0.57 \mu\text{V}, \text{SE} = 0.32$ ). For students with dyslexia, the sustained negativity at frontal sites was largest in the word learning phase ( $-3.75 \mu\text{V}, \text{SE} = 0.36$ ), intermediate in the semantic task ( $-2.79, \text{SE} = 0.49$ ; Tukey test:  $p < .001$ ) and smallest in the matching task ( $-1.45, \text{SE} = 0.57$ ; Tukey test:  $p < .001$ ). For skilled readers, it was more negative in the learning phase ( $-2.81 \mu\text{V}, \text{SE} = 0.49$ ) and in the semantic task ( $-2.30 \mu\text{V}, \text{SE} = 0.52$ ; Tukey test:  $p = .44$ ) than in the matching task ( $-0.71 \mu\text{V}, \text{SE} = 0.42$ ; Tukey test for each comparisons:  $p < .001$ ; Group x Task x Anterior-Posterior:  $F(4,120) = 3.07, p < .02$ ; effect size:  $\eta^2 = 0.05$  see Figure 6).



**Figure 6.** Grand averages across participants (students with dyslexia and skilled readers) and conditions are overlapped for the word learning phase (black line), the matching task (red line) and the semantic task (blue). ERPs are illustrated for nine recording sites of interest (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4).

#### 4. Discussion

The main aim of this experiment was to determine the consequences of phonological deficits, typically encountered in children and in adults with dyslexia (Elbro et al., 1994; Martin et al., 2010; Ramus, 2003; Saksida et al., 2016), on novel word learning. We aimed at disentangling two main hypotheses. Following the “phonetic-phonological-lexical continuity” or “cascading” hypotheses (Cooper & Wang, 2012, 2013; Dittinger et al., 2016, 2017; Wong & Perrachione, 2007), deficits in phonological processing should negatively impact the level of performance in the matching and semantic tasks. By contrast, the semantic compensation hypothesis (Arnbak & Elbro, 2000; Cavalli et al., 2016a; 2016b; 2017; Elbro & Arnbak, 1996; Haft et al., 2016; Martin et al., 2013) predicts that students with dyslexia may have developed knowledge and skills to cope with their phonological deficits so that their level of performance in the matching and semantic tasks would be similar to skilled readers. Results are discussed below in light of these two hypotheses.

##### *4.1. Evidence for persisting phonological deficits in university students with dyslexia*

In line with previous results (for example, Cavalli & al., 2018; Elbro et al., 1994; Ramus et al., 2003; Martin et al., 2010, see also the meta-analysis by Swanson & Hsieh 2009), students with dyslexia showed persistent phonological deficits, as evidenced by higher error rates than skilled readers in the four phonological tasks. While between-group differences seemed larger in the duration, pitch and aspiration tasks than in the voicing task, the Group by Task interaction was not significant (see Figure 2). Thus, these results clearly showed that several components of phonological processing were still impaired in the group of university students with dyslexia tested here. Moreover, results of a power analysis

1 showed that 34 participants are needed to detect an effect with 80% power. Since 32  
2 participants were tested in our experiment, we are confident that the effects that we report  
3 are reliable. Interestingly, for all participants, the aspiration and pitch tasks were more  
4 difficult than the voicing and duration tasks, as reflected by higher error rates. This finding is  
5 not surprising since non-native phonological contrasts, such as aspiration and pitch, that are  
6 not relevant to discriminate phonological word forms in the French phonemic system, are  
7 typically more difficult to perceive than native contrasts, such as voicing (Tyler et al., 2014).  
8 Nevertheless, the ability to discriminate non-native phonological contrasts vary according to  
9 individual differences and training (Sadakata & McQueen, 2013). For instance, using the  
10 same syllables as here, Dittinger et al. (2018) showed that professional musicians were more  
11 sensitive than non-musicians to aspiration contrasts with no difference for voicing contrasts.  
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#### 28 *4.2. Word learning phase: similar processes in students with dyslexia and skilled readers*

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32 Results in the Learning phase for skilled readers replicated those found by Dittinger et  
33 al. (2016), with a fast development of the N200 component that increased from block 1 to  
34 block 2, that is after only ten repetitions of each association. These results extend to the  
35 N200 component, previous findings with the N400 component, showing fast brain plasticity  
36 when participants are learning the meaning of novel words through a limited number of  
37 repetitions (Borovsky et al., 2010; 2012; Batterink et Neville, 2011). The N200 component  
38 has been described in different types of categorization tasks and, in phonological  
39 categorization tasks (Connolly et Phillips, 1994; Dittinger et al., 2018; Van Den Brink et al.,  
40 2001). In this context, increased N200 amplitude from block 1 to block 2 of the word  
41 learning phase may reflect enhanced categorization of the novel words based on their  
42 phonological components.  
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Importantly for our present goal, the increase in N200 amplitude from block 1 to Block 2 was not significantly different for students with dyslexia and for skilled readers (no Group by Block interaction). This finding is somewhat surprising based on the results reported both in the phonological pre-tests and in the four phonological tasks described above, evidencing clear phonological deficits in students with dyslexia. It may be that the different processes involved in novel word learning override between-group differences in phonological processing or that word repetition did facilitate word learning equally well in both groups of participants. Previous results already showed semantic knowledge to be actively used to stabilize phonological forms when participants are learning new words. For instance, Angwin, Phua and Copland (2014) showed that the N400 component was more negative when the meaning of novel words was learned from their semantic attributes than from proper names giving no semantic information. Similarly, Savill, Ellis and Jefferies (2017) demonstrated the importance of semantic knowledge to help correctly recall phonological information. Thus, to learn the meaning of novel words, students with dyslexia may use the semantic information derived from the picture-word associations as well as skilled readers. An argument in favor of this interpretation is that an N400 component also developed in the learning phase, that was not significantly different between the two groups of participants and that was larger over fronto-central than over parietal sites. This frontal scalp distribution has been taken as a signature of the learning processes, when participants mobilize frontal resources to extract word meaning from sentence contexts (Borovsky et al., 2010; Mestres-Missé et al., 2007), from statistical learning (François et al., 2017) or from picture-word associations (Dittinger et al., 2016; 2017). It possibly reflects the formation of new associations in working or short-term memory (Hagoort, 2014) and the building-up of word

1 representations in episodic memory (Rodriguez-Fornells et al., 2009; Wagner et al., 1998). It  
2 may also be that there is spatial and temporal overlap between the N200 and the N400, two  
3 components that are often difficult to dissociate. However, as noted by Nieuwland (2019),  
4 evidence for dissociating the N200 and N400 components is stronger when the two  
5 components are clearly visible in the waveforms which is the case in our experiments (see  
6 Figures 3, 4 and 5). In sum, there was no evidence in the word learning phase that the  
7 phonological deficits evidenced in the phonological tasks impede learning the meaning of  
8 novel words through picture-word associations in students with dyslexia.  
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21 *4.3. Mixed evidence for the cascading and compensation hypotheses in the matching and*  
22 *semantic tasks: behavioral data*  
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27 Interestingly, the pattern of results was clearly different in the matching and semantic  
28 tasks, with no between-group differences in the semantic task (either on error rates or on  
29 response times), but with lower level of performance (both on error rates and on response  
30 times, no speed-accuracy trade-off) for students with dyslexia than for skilled readers in the  
31 matching task. Therefore, these behavioral results provided mixed evidence for the  
32 compensation and cascading hypotheses. In the matching task, the overall lower level of  
33 performance of students with dyslexia compared to skilled readers is in favor of the  
34 “phonetic-phonological-lexical continuity” or “cascading” hypothesis (Cooper & Wang, 2012,  
35 2013; Dittinger et al., 2016, 2017; Wong & Perrachione, 2007), following which the  
36 persistent phonological deficits in students with dyslexia impeded them to build clear  
37 representations of the novel words and to decide whether or not they matched previously  
38 learned associations. By contrast, new pictures, not seen before in the experiment, were  
39 presented in the semantic task and participants had to decide whether they were  
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semantically related or unrelated to the newly learned words. This task more likely reflects semantic priming from new to old related pictures in semantic memory. Thus, in line with the semantic compensation hypothesis (Cavalli et al., 2017a; Schiff et al., 2016; 2019; Van der Kleij et al., 2019), these results suggest that students with dyslexia used semantic knowledge to compensate for their phonological deficits and reach a level of performance similar to skilled readers. However, results of power analyses showed that a total of 48 (for error rate) and 62 (for RTs) participants in the semantic task and of 44 participants (both error rate and RTs) in the matching task would be needed to detect effects with 80% power. Since we tested 32 participants in our experiment, the statistical power is low and more evidence is needed to make strong conclusions.

#### *4.4. Students with dyslexia and control readers use similar knowledge in the semantic task*

Evidence that both students with dyslexia and skilled readers used similar knowledge in the semantic task is that both groups showed reversed semantic priming effects on error rates. While semantically related words are typically associated with fewer errors and faster response time than unrelated words (Meyer & Schvaneveldt, 1971), the present results showed more errors to semantically related than to semantically unrelated words. This result was already reported by Dittinger et al. (2016) and was interpreted as a response bias toward rejection. When the task is difficult (the overall error rate across participants is higher in the semantic task (33%) than in the matching task (25%)), response uncertainty is high, and participants are more likely to consider words as semantically unrelated than semantically related to the new pictures. By contrast, response times differences conformed to the classic semantic priming effect, with faster response times to semantically related than unrelated pictures. Since response times were analyzed for correct responses only,

1 these results confirmed that words that were correctly categorized as semantically related  
2 benefitted from semantic priming. In other words, these results suggest that new pictures  
3 (never seen in the experiment) activated the newly formed representations in semantic  
4 memory of related pictures seen in the learning phase and in the matching task, thereby  
5 facilitating the processing of the associations with the novel words.  
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13 Another interpretation is that students with dyslexia benefitted more from the mere  
14 repetition of the picture-word associations in the word learning phase and in the matching  
15 task, thereby allowing them to reach the same level of performance as skilled readers in the  
16 semantic task. This would suggest that dyslexic participants did not use different knowledge  
17 than skilled readers to learn the meaning of novel words but rather, that they were slower in  
18 learning the associations, thereby needing more repetitions to reach a level of performance  
19 similar to skilled readers. This interpretation is in line with previous results from Smith-Spark  
20 and Fisk (2007) who reported that integrating novel task demands was more problematic for  
21 adult students with dyslexia than for skilled readers.  
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#### 37 *4.5. Match and mismatching words are associated with differences in the ERPs but not in* 38 *behavior* 39 40 41 42

43 In contrast to the semantic task, results in the matching task showed no significant  
44 differences, either on error rates or on response time, between words that matched or  
45 mismatched with the pictures. It is therefore unclear if participants, whether students with  
46 dyslexia or skilled readers, could discriminate the two types of words and more generally,  
47 whether they had learned the novel picture-word associations. Interestingly, however, ERPs  
48 revealed contrasting information. As expected, based on previous results in matching tasks  
49 (Dittinger et al., 2016), both the N200 and the N400 components were significantly more  
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1 negative to mismatch than to match words, thereby showing that participants were able to  
2 retrieve some information related to the picture-word associations from episodic memory  
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4 (Rodriguez-Fornells et al., 2009). While for the N200, this difference was widely distributed  
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6 across scalp sites, for the N400 component it was localized over parietal sites (see Figure 4).  
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8 This parietal scalp distribution, that corresponds to the typical distribution of the N400 for  
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10 known words (Bentin et al., 1985; Kutas et al., 1988) is taken as evidence that the meaning  
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12 of novel words has already been integrated into semantic memory (Dittinger et al., 2016;  
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14 Borovsky et al., 2012; Batterink & Neville, 2011; Mestres-Missé et al., 2007). Finally, and in  
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16 line with previous results, the LPC was more positive to mismatch than to match words,  
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18 possibly because mismatching words were less expected than matching words (Besson et al.,  
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20 1992), because they required more demanding retrieval processes (Batterink and Neville,  
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22 2011) or because they have not been fully lexicalized (Bakker et al., 2015). In sum, as shown  
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24 by previous results in auditory learning, the discrepancy between results at the behavioral  
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26 and electrophysiological levels in the matching task reveals that changes in the ERPs can  
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28 occur rapidly during training, before changes can be seen in behavior (Tremblay et al., 1998).  
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#### 31 *4.6. Students with dyslexia mobilize more neural resources to reach the same level of* 32 *performance than skilled readers in the semantic task* 33 34 35 36 37 38

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May be most importantly regarding the main aim of this study, results revealed no significant between-groups differences, either in the matching task or in the semantic task, on the N200 and N400 components. These findings are in line with the semantic compensation hypothesis in dyslexia and more generally with the conscious compensation hypothesis proposed by Nicolson & Fawcett (1990) to overcome automatization deficits. Interestingly, however the sustained negativity over frontal sites was more negative for

1 students with dyslexia than for skilled readers. By contrast, the LPC over parietal sites was  
2 more positive for skilled readers than for students with dyslexia. This contrastive pattern of  
3 results is in line with the interpretation following which N400 and sustained negativities over  
4 frontal sites reflect the on-going demanding processing of forming new associations  
5 (Borovsky et al., 2010, Mestres-Misse et al., 2007; Dittinger et al., 2016, 2017). Results of the  
6 between-tasks comparison add support to this interpretation in showing that frontal  
7 negativities were largest in the word learning phase and in the semantic task that were more  
8 demanding (high error rates in the semantic task) than the matching task (see Figure 6).  
9 Thus, the more negative sustained negativities over frontal sites in students with dyslexia  
10 than in skilled readers possibly reflect the fact that the semantic task was more resource-  
11 demanding for students with dyslexia. This interpretation is in line with previous ones in  
12 terms of compensation mechanisms (Nicolson & Fawcett, 1990; Smith-Spark and Fisk, 2007)  
13 and with results from Robichon et al. (2002) showing that adults with dyslexia mobilize more  
14 resources than skilled readers to integrate the meaning of congruous words into sentence  
15 contexts. By contrast, more positive LPC over parietal sites for skilled readers than for  
16 students with dyslexia possibly reflects faster integration into semantic memory of newly  
17 learned words (Batterink & Neville, 2011) and/or more controlled semantic access to newly  
18 formed word representations (Bakker et al., 2015. In sum, students with dyslexia may  
19 mobilize more frontal resources to perform the tasks at hand and, in line with the semantic  
20 compensation hypothesis and more generally with the conscious compensation hypothesis  
21 (Nicolson & Fawcett, 1990), this would allow them to perform as well as skilled readers in  
22 the semantic task.

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Between-group differences in the scalp distribution of the N400 component in the matching task also suggest that students with dyslexia mobilize more neural resources than skilled readers. In skilled readers, and in contrast to the typical parietal right-hemisphere predominance of the N400 component in the visual modality (Kutas et al., 1988), the distribution of the auditory N400 was slightly larger over the left compared to midline and right hemisphere locations (Holcomb and Neville, 1990). No such inter-hemispheric differences were found for students with dyslexia who showed an equipotential distribution of the N400 component across scalp sites. Again, the finding that students with dyslexia equally recruited the two hemispheres possibly reflects that more neural resources are mobilized to perform the task at hand (see Silva et al., 2016, for a similar interpretation).

#### 4.7. Limitations

The main hypothesis of no between-group differences in the matching and semantic task could be problematic in that it implies accepting the null hypothesis. However, we also predicted between-groups differences in the phonological tasks. Results were in line with this hypothesis. Moreover, even if at the behavioral level, results showed no significant between-group differences in the semantic task (possibly because of lack of statistical power), such differences were significant in the matching task. Finally, analyses of the ERPs revealed between-group differences for the sustained frontal negativities and for the LPC.

In the discussion above, we focused on the components of main interest, N200, N400, sustained negativities and LPC, that have been examined in previous word learning experiments (Bakker et al., 2015; Borovsky et al., 2010, Mestres-Misse et al., 2007; Dittinger et al., 2016, 2017; Batterink & Neville, 2011). However, significant differences were also found on the amplitude of the P200 component that was less positive in block 1 than in

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block 2 in the word learning phase and that was more positive to match than to mismatch words in the matching task. These modulations of P200 amplitude possibly influenced the development of later components, in particular the N200 component. This may consequently impact on the interpretations proposed above. However, these P200 results first need to be replicated to better understand how they possibly influenced later components.

### 5. Conclusions

Although results in the matching task suggest a cascading influence of phonological deficits on the formation of picture-word associations in episodic memory in students with dyslexia, taken together behavioral and electrophysiological results are more in favor of the semantic compensation hypothesis. As expected, students with dyslexia made more errors than skilled readers in the phonological tasks. By contrast, the between-group differences, either on error rates or on response time, were not significant in the semantic task. Similar results were found at the electrophysiological level with analyses of the ERPs data showing no significant between-group differences in the matching and semantic tasks, except for some differences in the sustained negativity, LPC and scalp distribution of the N400 component that may reflect that students with dyslexia needed more neural resources to perform the task at hand. Importantly, results in skilled readers largely replicated those found previously using the same design with an independent group of participants (Dittinger et al., 2016). An interesting perspective for future studies would be to re-test participants after a short (e.g., one day) and a long (e.g., one month) delay to determine whether consolidation processes (Bakker et al., 2015) would also be similar for university students with dyslexia and for skilled readers.

1 The concept of compensation (Nicolson & Fawcett, 1990) has received little empirical  
2 attention and there is currently no agreed technical definition of compensation regarding its  
3 behavioral, cognitive and neural characteristics. Recently, Livingstone and Happé (2017)  
4 proposed that: “compensation contributes to a mismatch between behavior and the  
5 relevant underpinning cognition, whereby a “compensated” individual’s behavioral  
6 presentation is better than would otherwise be expected based on their underlying cognitive  
7 profile“ (page 731). In line with this working definition, we showed that in order to learn  
8 novel word meaning, students with dyslexia performed the semantic task better than  
9 predicted based on their impaired phonological skills (as revealed by results at the  
10 phonological pre-tests and at the phonological categorization tasks). In fact, no significant  
11 between-groups differences, either in behavior or in electrophysiological data, were found in  
12 the semantic task, except that students with dyslexia seemed to activate more frontal  
13 resources when performing this task. This set of data suggest that high-achieving individuals  
14 with dyslexia (university students) may normally increase their vocabulary skills and may  
15 limit the negative effects of the phonological deficits they suffer from, by activating semantic  
16 knowledge already stored in memory (that is, connections between semantically related  
17 words). This could explain why previous results showed that their vocabulary skills are not  
18 impacted by their phonological deficits (Cavalli et al., 2016). One may hypothesize that one  
19 of the main characteristics of the cognitive compensation in these individuals depends on  
20 the use of top-down processes (not only activating semantic knowledge but also information  
21 provided by the context of the tasks). This proposal is in line with the semantic binding  
22 hypothesis by Patterson et al. (1994) and recently tested by Savill et al. (2017) according to  
23 which when learning new words, semantic knowledge would increase the stability of  
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phonological trace very early in the process by virtue of bidirectional connections between the semantic and phonological systems. More data are needed to test this hypothesis and if it is to be confirmed, new forms of remediation in dyslexia could then be considered.

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