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The nature of the phonological processing in French dyslexic children: evidence for the phonological syllable and linguistic features' role in silent reading and speech discrimination

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Abstract This study investigated the status of phonological representations in French dyslexic children (DY) compared with reading level- (RL) and chronological age-matched (CA) controls. We focused on the syllable's role and on the impact of French linguistic features. In Experiment 1, we assessed oral discrimination abilities of pairs of syllables that varied as a function of voicing, mode or place of articulation, or syllable structure. Results suggest that DY children underperform controls with a 'speed-accuracy' deficit. However, DY children exhibit some similar processing than those highlighted in controls. As in CA and RL controls, DY children have difficulties in processing two sounds that only differ in voicing, and preferentially process obstruent rather than fricative sounds, and more efficiently process CV than CCV syllables. In Experiment 2, we used a modified version of the Colé, Magnan, and Grainger's (Applied Psycholinguistics 20:507–532, 1999) paradigm. Results show that DY children underperform CA controls but outperform RL controls. However, as in CA and RL controls, data reveal that DY children are able to use phonological procedures influenced by initial syllable frequency. Thus, DY children process syllabically high-frequency syllables but phonemically process low-frequency syllables. They also exhibit lexical and syllable frequency effects. Consequently, results provide evidence that DY children performances can be accounted for by laborious phonological syllable-based procedures and also degraded phonological representations.

Keywords Dyslexia · Phonological processing · Reading · Syllable · Syllable frequency · Voicing

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Introduction

Developmental dyslexia is described as a neurobiological disorder that induces long-lasting literacy learning difficulties (e.g., Ramus, 2003) with prevalence rates ranging from 5 to 17.5% (Shaywitz & Shaywitz, 2005). Dyslexic individuals also fail to acquire proficiency in reading skills despite adequate intellectual and educational backgrounds. It is now well accepted that developmental dyslexia is primarily associated with a phonological processing deficit that underpins the cognitive disorder (e.g., Ziegler & Goswami, 2005). Thus, the phonological deficit hypothesis provides a unifying causal framework at the cognitive level to account for difficulties faced by dyslexic individuals (e.g., Ramus, 2001).

One recurrent hypothesis is that dyslexia results from under-specified and degraded phonological representations (e.g., Boada & Pennington, 2006; Elbro & Jensen, 2005; Snowling, 2001; Swan & Goswami, 1997). Phonological disorders are thought to manifest themselves as multi-dimensional difficulties (Ziegler, Castel, Pech-Georgel, George, Alario, & Perry, 2008) that include poor performances in phonological awareness-that requires the manipulation of speech sounds, e.g., phoneme, rime, syllable, orthographic coding, rapid automatic naming (RAN), and phonological short-term memory (pSTM), whatever the concerned subtype of dyslexia (Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000). More specifically, dyslexic individuals systematically have poor performances when they are required to map graphemes (orthography) and phonemes (phonology). Reading difficulties also stem from an underlying deficit in grapheme-to-phoneme correspondences (GPCs) learning and handling (e.g., Sprenger-Charolles et al., 2000). As reviewed by Scarborough (1998) or Vellutino, Fletcher, Snowling and Scanlon (2004), disorders in acquiring phonological awareness and orthographic coding skills are rooted in poor phonological representations.

However, as emphasized by Ziegler and Goswami (2005; see also Seymour, Aro, & Erskine, 2003), phonological awareness and GPCs develop faster in transparent (rather than in a opaque) languages and vary in the size of sublexical reading units: large reading units (e.g., rime) are preferred in opaque orthographies such as English, while small reading units (e.g., phoneme) are preferred in transparent orthographies such as German. Then, Snowling (2001) reminded that phonological awareness deficits in dyslexic individuals are less marked in transparent languages than in opaque languages.

Paradoxically, the nature of the under-specified and degraded phonological representations remains unclear (Ramus, 2001). Although the phonological deficit hypothesis does represent the most reliable correlate of reading disability in developmental dyslexia (e.g., Marshall, Snowling, & Hulme, 2001; Ramus, Rosen, Dakin, Ray, Castellote, White, & Frith, 2003), French studies were rarely interested in the syllable's role and have never focused on the syllable frequency in dyslexics, whereas French phonological and phonetic properties suggest that French is a syllable-timed language (e.g., Altmann, 1997).

This paper presents a two-stage study of the phonological representations in dyslexic children. The issue raised by the present article is to determine whether reading-impaired children are able to use phonological grapho-syllabic units and are sensitive to French language-specificities. We deemed it interesting to conduct two experiments to investigate: 1) oral discrimination abilities of minimal pairs of syllables that varied as a function of voicing, mode or place of articulation, or syllable structure (Experiment 1); 2) whether the syllable (Manulex-infra, Peereman, Lété, & Sprenger-Charolles, 2007) and word frequency (Manulex; Lété, Sprenger-Charoles, & Colé, 2004) influence the resort to the syllable as the privileged phonological reading unit in French (Experiment 2) in dyslexic children (DY) compared with chronological age-matched (CA) and reading level-matched (RL) controls. The major interest of the present study was to examine the syllable's role in French normal- and impaired-reading children during reading acquisition in both spoken and written tasks, considering that few studies out of this nature have been carried out.

Speech-specific deficit and categorical perception

The phonological deficit hypothesis implies that the phonological deficits would arise from a specific impairment of phonological representations that they are under-specified and/or degraded. There is much debate in whether difficulties in both phonological awareness and orthographic coding basically result from sensory or linguistic impairments (Ramus, 2003). Among the wide range of phonological deficits evocated to account for dyslexic individuals' phonological disorders, one hypothesis has recently extended the influential theory of a specific auditory processing deficit in dyslexic individuals (Tallal, 1980; see Farmer & Klein, 1995 for a review). Recent theoretical and empirical arguments have extended the specific temporal and spectral deficits in sound resolution to focus on a speech-specific failure in dyslexic individuals' phonological representations. Some studies have suggested that some dyslexic individuals (roughly 50%; Ramus et al., 2003) encounter a deficit in representing, discriminating, and categorizing sounds with rapid formant transitions. More specifically, such a deficit has held many researchers' attention because it could cause specific impairments in categorical perception on pairs of syllables differentiated by an acoustic phonetic feature (e.g., voicing), especially when this acoustic phonetic event is used as cue for phonemic contrasts (e.g., Adlard & Hazan, 1998; Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Breier, Gray, Fletcher, Diehl, Klaas, Foorman et al., 2001; Mody, Studdert-Kennedy, & Brady, 1997; Nittrouer, 1999; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Veuillet, Magnan, Écalle, Thai-Van, & Collet, 2007; Werker & Tees, 1987).

For instance, recent works demonstrated that dyslexics have poorer performances in categorical perception than normal readers, whether regarding chronological or lexical age-matched controls (e.g., Bogliotti et al., 2008). Categorical perception “corresponds to the degree to which acoustic differences between variants of the same phoneme are less perceptible than differences of the same acoustic magnitude between two different phonemes” (Serniclaes et al., 2004, p.337). Thus, dyslexic individuals outperformed controls in within-boundaries perception, whereas they underperformed controls in between-boundaries perception (e.g., Serniclaes et al., 2001). This result was interpreted as evidence that dyslexic individuals have lower categorical perception ability but possesses greater sensitivity for contextual acoustic phonetic cues. This pattern was further tested in Bogliotti et al.'s (2008) (also see Serniclaes et al., 2004) work that demonstrated that dyslexic individuals resort to an allophonic mode of speech perception. Even though phonemic categories that are irrelevant for phoneme perception in the linguistic environment are usually deactivated early in life (e.g., Werker & Tees, 1984), dyslexic children would maintain a high within-category sensitivity to contextual phonemic contrasts. An allophonic mode of speech perception would increase and extend the one-to-one mapping load during GPCs (e.g., Bogliotti et al., 2008) and would probably be amplified in opaque orthographies. In fact, this would affect the GPCs mapping because dyslexic children who preferentially process allophones rather than phonemes would experience difficulties in attributing a unique grapheme to a unique phoneme that may belong to different categories of the linguistic environment.

Recently, Ramus and Szenkovits (2008; see also Szenkovits & Ramus, 2005) have qualified this point of view. They argued that dyslexic individuals suffer from difficulties in accessing phonological representations when memory load is constrained by environmental interferences (e.g., speed, noise…), such as in categorical perception tasks in which poor phonemic representations are not systematically highlighted (e.g., Rosen, 2003; Rosen & Manganari, 2001). Furthermore, recent studies (e.g., Rosen, 2003; Ramus, 2003; White, Milne, Rosen, Hansen, Swettenham, Frith et al. 2006) have challenged that auditory deficits, and in extenso speech-specific deficits, are causally related to dyslexic individuals' phonological impairments but have suggested that they simply may occur in association with them.

However, number of studies also have attempted—and sometimes succeeded—in linking poor phonological awareness and poorly specified phonological representations as underlying poor performances in speech discrimination and identification (e.g., Breier, Fletcher, Denton, & Gray, 2004; Mody et al., 1997; Serniclaes et al., 2001). For instance, recent studies conducted in French were interested in implications of intensive audio-visual training focusing on voicing feature to improve phonological skills (e.g., Bedoin, 2003; Écalle, Magnan, Bouchafa, & Gombert, 2009; Magnan, Écalle, Veuillet, & Collet, 2004; Veuillet et al., 2007). Results have evidenced that such training improved categorical perception—i.e., better performances in identification and discrimination tasks—and significantly boosted short- and medium-term performances in GPC manipulations.

Impaired-reading acquisition and the syllable's role

According to Ramus (2001), there is insufficient evidence to clearly identify and characterize the nature of these phonological impairments as many levels of representation and processing are simultaneously involved. Actually, few developmental studies were dedicated to the syllable's role in French normal-reading children (e.g., Chétail & Mathey, in press; Bastien-Toniazzo, Magnan, & Bouchafa, 1999; Colé, Magnan, & Grainger, 1999; Doignon & Zagar, 2006; Maïonchi-Pino, Magnan, & Écalle, 2010; Sprenger-Charolles & Siegel, 1997). Nevertheless, linguistic data support that French language is a syllable-timed language (see Spencer, 1996, for a review), insomuch as phonemes within the initial syllable are acoustically unclear and therefore difficult to identify separately because of their coarticulation (e.g., Altmann, 1997).

To our knowledge, only Colé and Sprenger-Charolles (1999) have examined the syllable's role in French-reading disabled children. They used a visual version of Mehler, Dommergues, Frauenfelder, and Seguí's (1981) segment detection task, that was adapted by Colé et al. (1999). In the visual version, participants had to decide whether a printed target (i.e., CV or CVC) appeared or not at the beginning of a printed test word whose first syllable was either CV or CVC. When participants more quickly detected a target exactly matched to the initial syllable of a subsequently displayed test word (e.g., PA in PARADE or PAR in PAR.TIR rather than PA in PAR.TIR or PAR in PA.RADE), results showed a crossover Target × Test word interaction; this observation was called *syllable compatibility effect* that reflects the use of a phonological grapho-syllabic processing. Otherwise, when participants more quickly processed a target as a function of its length (i.e., CV target is faster responded than CVC target whatever the initial syllable of a test word), results demonstrated a *target length effect* that reflects the use of a phonological grapho-phonemic processing or a visual serial left-to-right processing. Authors also manipulated lexical frequency, using an old orthographic frequency scale (Dubois-Buyse's scale; Ters, Mayer, & Reichenbach, 1977).

Prior to the Colé and Sprenger-Charolles' (1999) study, Colé et al. (1999) gathered empirical data in French first graders tested twice. After 6 months of GPCs learning, results showed a *target length effect* that was interpreted as a phonological grapho-phonemic processing instead of a letter-by-letter processing because all the children were taught with a GPC-based method. After 1 year of GPC learning, results spotlighted a *syllable compatibility effect* regarding the reading level (i.e., only in good readers), which meant that children used a phonological grapho-syllabic processing. Colé et al. (1999) also proposed a theoretical design compatible with the developmental course hypothesized by Seymour and Duncan (1997) who proposed that small units such as phoneme are involved firstly during the reading acquisition when the children are taught to GPCs before being able to use larger units such as syllable. Thus, the explicit teaching of GPCs allows children to develop connections between letters and sounds. As soon as GPCs are explicitly taught, children automatically use the grapho-phonemic processing, and then they try to extract larger units than phonemes (e.g., grapho-syllabic processing) corresponding to early implicit syllabic structures developed through extensive contacts with the spoken language (e.g., Goslin & Floccia, 2007), whereas phonemic awareness only develops with explicit GPC teaching. From a cognitive point of view, syllabic segmentation (e.g., *mardi* 'Tuesday' into /mar/+/di/) is less constraining than phonemic segmentation (e.g., /m/+/a/+/r/+/d/+/i/).

Maïonchi-Pino et al.'s (2010) developmental study from first to fifth grades also used the Colé et al.'s (1999) paradigm. However, they addressed the issue of syllable and word frequency in French children. They used the children-specific Manulex database (Lété et al. 2004) for word frequency and Manulex-infra database (Peereman et al., 2007) for syllable frequency. Results showed that phonological processing progressed from phonological grapho-phonemic to phonological grapho-syllabic processing, primarily influenced by syllable frequency: in first and third graders, the *syllable compatibility* effect was restricted to high-frequency syllables, whereas the *target length effect* emerged with low-frequency syllables. In fifth graders, high- and low-frequency targets triggered a *syllable compatibility effect*. Moreover, a syllable frequency effect and a word frequency effect were significant only in third and fifth graders. Maïonchi-Pino et al. (2010) concluded that syllable frequency did not inhibit the prelexical access (see Chétail & Mathey, in press, for a review), on the contrary, the high-frequency syllables gained phonological processing as they would be stored as precompiled gestures developed through repetitive GPC configurations, whereas low-frequency syllables would benefit from sequential GPCs.

Finally, Colé and Sprenger-Charolles (1999) showed that dyslexic children did not use syllable-sized units, but rather a serial letter-by-letter processing (i.e., a *target length effect* emerged). As dyslexic children were impaired in phonological tasks, a phonological grapho-phonemic processing was excluded. Furthermore, a word frequency effect was obtained (i.e., frequent words were overall processed faster than rare words). According to these authors, this letter-by-letter procedure—and the word frequency effect—might be built from under-specified phonological representations and from the extraction of incomplete orthographic regularities knowledge developed through repeated exposures to written language.

To conclude, an early and long-lasting syllable-based segmentation emerges in French beginning readers, as soon as at the end of the first year of reading instruction (Bastien-Toniazzo et al., 1999; Colé et al., 1999; Maïonchi-Pino et al., 2010), primarily influenced by the initial syllable frequency. However, we stated that none of these studies considered the importance of the initial syllable frequency and neglected the use of children-based lexical frequency databases in French dyslexic children (DY).

Experiment 1

Experiment 1 was designed to investigate the status of phonemic and linguistic representations through oral discrimination abilities of minimal pairs of syllables in DY children compared with French CA and RL controls. Our purpose was twofold[1]. First, we aimed at replicating previous data showing that DY children are impaired in processing between-category discrimination when they have to distinguish sounds differing on voicing (e.g., Masterson, Hazan, & Wijayatilake, 1995; Reed, 1989; Serniclaes et al., 2001). Accordingly, as between-category discrimination is problematic in DY children (e.g., Serniclaes et al., 2004), we expected that DY children would perform the 'identical' condition better than the 'different' condition. Second, we studied how mode and place of articulation and syllable structure are processed when children have to detect identical or different pairs of syllables. According to Clements (1990), CV syllables would be processed better than CCV syllables because CV syllables are predominant in French (55%; Wioland, 1985) and are described as optimal in terms of structure and sonority. Besides, Sprenger-Charolles and Siegel (1997) or Bastien-Toniazzo et al. (1999) demonstrated that French-beginning readers frequently simplify complex consonant clusters (e.g., CCV, CVC) into the optimal CV structure in reading aloud. Similarly, we hypothesized that obstruent sounds would improve performances because fricative sounds are acquired later (e.g., Rondal, 1997) and induce more confusions than obstruent ones (e.g., Masterson et al., 1995). Finally, we predicted that performances would be related to reading skills; CA controls would outperform RL controls and DY children. However, as DY children experienced repeated oral and written exposures longer than RL controls, RL controls would underperform DY children. However, whatever the group of children, the distinction between two syllables that differed in a single acoustic phonetic feature such as voicing would be more problematic than the processing of two syllables that differed in place of articulation or in voicing + place of articulation.

Participants

Fifteen DY participated in this experiment. DY children (mean chronological age, 121 months, *SD*=12 months; mean reading age, 89 months, *SD*=5 months) were diagnosed as having dyslexia (i.e., mixed dyslexia with major phonological disorders) by neuropsychologists and enrolled in pediatric hospital services dedicated to children with learning disabilities. DY children were compared to 15 CA children (mean chronological age, 124 months, *SD*=12 months; mean reading age, 137 months, *SD*=15 months) and to 15 RL children (mean chronological age, 81 months, *SD*=3 months; mean reading age, 89 months, *SD*=4 months). They were all tested once. All the children were different from the previous experiment. All of the children were French native speakers, middle class, right-handed, and were taught reading with GPC rules. They had normal or corrected-to-normal vision.

[1] We acknowledge that we did analogies between the categorical perception task and the oral discrimination task to hypothesize, although both tasks were quite different in their courses and in their materials.

Method

Word reading test

Children individually completed a French standardized word reading test to ensure that they had no reading disorder. We used TIMÉ 2 (Écalle, 2003) to select RL controls and TIMÉ 3 (Écalle, 2006) to select CA controls. These tests assessed the reading accuracy and the orthographic knowledge level. No analysis was conducted on the scores. The scores showed expected reading age-based profiles. Children were matched to corresponding DY children by the scores they obtained in the Alouette test (Lefavrais, 1965; see Écalle, 2006 to overview the correlations between performances in TIMÉ tests and Alouette test). Profiles are described in Table 1.

Material and design

Stimuli were partially extracted from a battery of tests built by Van Reybroeck (2003). Stimuli included 16 monosyllabic sounds in which half had a simple CV structure (e.g., /bu/) and the other half had a complex consonant cluster CCV structure (e.g., /bRu/). Initial consonants—or cluster—were always followed by the vowel /u/. In CCV structures, prevocalic consonant was always the same sonorant consonant (i.e., /R/). CV and CCV sounds were fairly subdivided into initial obstruent and fricative consonants. Half of the obstruent consonants and half of the fricative consonants were voiced, whereas the other halves were unvoiced. All of the phonemes within the sounds exist in French. Sounds were systematically administered by pairs. We shared sounds into two experimental conditions: 'identical' and 'different' (see Appendix A). In the 'identical' condition, pairs of sounds were strictly identical (e.g., /bu/ followed /bu/). Each pair was administered three times. In the 'different' condition, pairs of sounds were systematically different: the difference could apply on the voicing of the first phoneme (e.g., /bu/ then /pu/), on the place of the articulation (e.g., /bu/ then /du/), or on both voicing + place of articulation (e.g., /bu/ then /tu/). Each pair was administered once. At last, 48 identical pairs and 48 different pairs were administered. Lexicality was controlled. We designed a four-experimental list experiment. Children encountered all the experimental conditions. Each experimental list was separated by a pause. The order of the presentation of the stimuli in each experimental list and the order of the presentation of each experimental list were randomized. Response times and errors were automatically recorded. The experimenter never intervened during the test. Experimental conditions are summarized in Tables 2 and 3.

Procedure

Children were tested in single, individual sessions. The script was designed and compiled with PsyScope 1.2.5 (Cohen, McWhinney, Flatt, & Provost, 1993). Experiment ran on a Macintosh iBook laptop computer. Children sat at roughly 57 cm from the screen in a partially sound-absorbent room. Sounds were administered through an Altec Lansing AHS 502i helmet. Sounds were previously recorded by a French native speaker, post-processed to delete interferences, sampled and then converted into Sound Designer II format at a 44,100 Hz rate in a 16-bit stereo with SoundForge 9.0 software. A vertically centered fixation cross (i.e., +) typed in 'Arial' font, size '48', was displayed during 500 ms on the screen. After disappearance of the fixation cross, the first sound was played and followed after a 250-ms delay by the second sound. Then, the next sequence followed after a 500-ms

Table 1 Detailed profiles of dyslexic children (DY), reading level (RL)- and chronological age (CA)-matched controls

Participant	Gender	Chronological age	Lexical age	Participant	Gender	Chronological age	Lexical age	Participant	Gender	Chronological age	Lexical age
S1	Boy	143	92	S16	Girl	82	91	S31	Boy	147	157
S2	Girl	126	96	S17	Boy	83	95	S32	Boy	131	159
S3	Boy	128	88	S18	Boy	81	92	S33	Boy	131	136
S4	Boy	115	94	S19	Girl	84	89	S34	Girl	115	126
S5	Boy	136	93	S20	Girl	82	95	S35	Girl	135	149
S6	Boy	131	91	S21	Boy	76	90	S36	Girl	133	137
S7	Boy	124	94	S22	Boy	84	94	S37	Boy	124	134
S8	Boy	126	92	S23	Boy	82	88	S38	Boy	128	145
S9	Girl	101	83	S24	Girl	78	85	S39	Girl	106	110
S10	Girl	130	86	S25	Girl	82	87	S40	Girl	135	148
S11	Boy	120	88	S26	Boy	87	90	S41	Boy	120	148
S12	Girl	116	80	S27	Boy	81	84	S42	Boy	122	133
S13	Girl	113	87	S28	Boy	80	86	S43	Girl	111	124
S14	Boy	109	88	S29	Boy	83	85	S44	Boy	113	137
S15	Boy	101	81	S30	Boy	75	81	S45	Boy	104	111
Mean		121.3	88.9			81.3	88.8			123.7	136.9
SD		12.2	4.9			3.1	4.2			12.2	14.8

Table 2 Sample of the experimental conditions used in experiment 1 in identical condition

Mode		Identical condition			
		Obstruent		Fricative	
Voicing		Voiced	Unvoiced	Voiced	Unvoiced
Syllable structure	CV	/bu/ then /bu/	/tu/ then /tu/	/vu/ then /vu/	/su/ then /su/
	CCV	/bRu/ then /bRu/	/pRu/ then /pRu/	/vRu/ then /vRu/	/fRu/ then /fRu/

delay. Children were instructed to decide as quickly and as accurately as possible whether the second sound was identical or not to the first sound. For right-handed preference, children had to press on 'a' or 'p' response keys, for 'identical' or 'different,' respectively. Children were also trained with a practice list that included four prototypical trials. No feedback was given.

Results

ANOVAs were carried out on the data using subjects ($F1$) and items ($F2$) as random variables on mean response times (RT) and errors (17.2% of the data). Only correct RT were included in the analyses. The correct RT were standardized (i.e., for each subject, the response times away from more or less two standard deviations (SD) were replaced by the mean RT of each subject (≈4.5% of the data)). We used the signal detection theory (SDT) to measure the sensibility thresholds (i.e., d' criterion). Descriptive data are summarized in Table 4.

Comparison of the three groups

One-way ANOVA was performed on the d' computed for each group. Results showed a main effect of Group, $F(2, 42)=10.66$, $p=0.0002$, $\eta^2=0.34$. A Student t test evidenced that CA controls sensitivity threshold was significantly higher ($d'=2.6$) than those of RL controls ($d'=2.0$) [$t[28]=3.70$; $p=0.0009$] and DY children ($d'=1.7$) [$t[28]=-4.06$; $p=0.0004$]. Difference between RL controls and DY children was not significant.

Table 3 Sample of the experimental conditions used in experiment 1 in different condition

Mode		Different condition					
		Obstruent			Fricative		
Opposition		Voicing	Place	Voicing + place	Voicing	Place	Voicing + place
Syllable structure	CV	/bu/ then /pu/	/bu/ then /du/	/bu/ then /tu/	/fu/ then /vu/	/fu/ then /su/	/fu/ then /zu/
	CCV	/bRu/ then /pRu/	/bRu/ then /dRu/	/bRu/ then /tRu/	/fRu/ then /vRu/	/fRu/ then /sRu/	/fRu/ then /zRu/

Table 4 Statistical descriptive data in Experiment 1 (mean response times (in milliseconds), standard error (below), and error rate) in RL and CA controls and DY children

			Obstruent		Fricative					Obstruent		Fricative					Obstruent		Fricative	
			CV	CCV	CV	CCV				CV	CCV	CV	CCV				CV	CCV	CV	CCV
RL	Identical	Voiced	1,582	1,554	1,577	1,497	CA	Identical	Voiced	1,262	1,378	1,229	1,237	DY	Identical	Voiced	1,917	1,925	1,945	1,872
			94	86	69	77				64	82	47	35				117	174	118	151
			6.7%	14.4%	14.4%	15.6%				3.3%	5.6%	10.0%	4.4%				14.4%	22.2%	23.3%	26.7%
			1,499	1,580	1,574	1,754				1,147	1,189	1,308	1,299				1,663	1,937	1,836	1,966
		Unvoiced	98	78	70	101			Unvoiced	34	41	53	52			Unvoiced	140	204	187	195
			7.8%	11.1%	12.2%	23.3%				3.3%	6.7%	8.9%	17.8%				12.2%	18.9%	16.7%	23.3%
			1,657	1,644	1,696	1,727				1,440	1,323	1,356	1,557				1,977	1,981	1,866	1,967
		Voicing	110	128	70	97			Voicing	56	61	53	122			Voicing	188	178	148	156
			16.7%	26.7%	28.3%	21.7%				18.3%	21.7%	13.3%	28.3%				33.3%	40.0%	26.7%	25.0%
			1,586	1,731	1,808	1,691				1,326	1,352	1,406	1,495				2,259	2,171	2,018	1,947
	Different	Place	94	133	161	75		Different	Place	44	65	55	72		Different	Place	227	169	198	145
			16.7%	23.3%	20.0%	30.0%				10.0%	18.3%	11.7%	21.7%				20.0%	11.7%	25.0%	21.7%
			1,697	1,948	1,674	1,851				1,297	1,404	1,369	1,431				2,104	2,040	1,911	2,142
		Voicing + place	117	144	127	107			Voicing + place	54	54	70	71			Voicing + place	190	188	161	174
			6.7%	26.7%	15.0%	25.0%				5.0%	13.3%	8.3%	18.3%				23.3%	21.7%	30.0%	25.0%

For the ‘yes’ and ‘no’ responses comparison,[2] a 2×2×2 within-subject factors (condition: identical vs. different; syllable structure: CV vs. CVC; mode: obstruent vs. fricative) and one between-groups factor (Group: DY, RL, and CA) mixed-model ANOVA was conducted on mean RT and errors. ANOVAs showed a significant main effect of Group in the RT analysis, $F1(2, 42)=14.84$, $p<0.0001$, $\eta^2=0.41$, and in the errors analysis, $F1(2, 42)=7.76$, $p=0.001$, $\eta^2=0.27$, (see below the separate condition comparisons). Furthermore, the ANOVAs revealed a main effect of condition exclusively in the RT analysis, $F1(1, 42)=42.86$, $p<0.0001$, $\eta^2=0.51$; overall, the identical condition was performed faster (1,576 ms) than the different condition (1,718 ms).

For the ‘yes’ responses (i.e., ‘identical’ condition), a 2×2×2 within-subject factors (syllable structure: CV vs. CVC; mode: obstruent vs. fricative; voicing: voiced vs. unvoiced) and one between-groups factor (Group: DY, RL, and CA) mixed-model ANOVA was carried out on mean RT and errors. ANOVAs revealed a significant main effect of Group in the RT analysis, $F1(2, 42)=14.80$, $p<0.0001$, $\eta^2=0.41$, $F2(2, 120)=183.61$, $p<0.0001$, $\eta^2=0.75$, and in the errors analysis, $F1(2, 42)=6.11$, $p=0.005$, $\eta^2=0.23$, $F2(2, 120)=13.94$, $p<0.0001$, $\eta^2=0.19$ (see Fig. 1); Student t tests highlighted that DY children responded slower (1,882 ms) and committed more errors (1.2) than CA controls (1,255 ms; 0.5) [$t[28]=10.45$; $p<0.0001$, $t[28]=5.83$; $p<0.0001$, respectively], and RL controls (1,577 ms; 0.8) [$t[28]=4.75$; $p<0.0001$; $t[28]=2.97$; $p=0.003$, respectively]; CA controls responded faster and made fewer errors than RL controls [$t[28]=-9.03$; $p<0.0001$, $t[28]=-3.29$; $p=0.001$, respectively]. The ANOVAs also revealed two additional significant main effects for the errors analysis: a main effect of syllable structure, $F1(1, 42)=4.40$, $p=0.04$, $\eta^2=0.10$, $F2(1, 120)=9.95$, $p=0.002$, $\eta^2=0.08$; and a main effect of mode, $F1(1, 42)=10.80$, $p=0.002$, $\eta^2=0.26$, $F2(1, 120)=5.64$, $p=0.02$, $\eta^2=0.04$; overall, CV sounds induced fewer errors (0.7) than CCV sounds (1.0), and obstruent sounds were better processed (0.6) than fricatives ones (1.0).

For the ‘no’ responses (i.e., ‘different’ condition), a 2×3 within-subject factors (syllable structure: CV vs. CVC; opposition: voicing vs. place vs. voicing + place) and one between-groups factor (Group: DY, RL, and CA) mixed-model ANOVA was carried out on mean RT and errors. ANOVAs showed a main effect of Group in the RT analysis, $F1(2, 42)=13.05$, $p<0.0001$, $\eta^2=0.38$, $F2(2, 132)=154.42$, $p<0.0001$, $\eta^2=0.70$, and in the errors analysis, $F1(2, 42)=3.44$, $p=0.04$, $\eta^2=0.14$, $F2(2, 108)=7.30$, $p=0.001$, $\eta^2=0.12$ (see Fig. 2); Student t tests attested that DY children responded slower (2,032 ms) and made more errors (1.0) than CA controls (1,396 ms; 0.6) [$t[28]=11.72$; $p<0.0001$, $t[28]=4.37$; $p<0.0001$, respectively]; CA controls also responded faster and committed fewer errors than RL controls (1,726 ms; 0.9) [$t[28]=-8.52$; $p<0.0001$, et $t[28]=-2.72$; $p=0.007$, respectively]. However, DY children only responded slower than RL controls [$t[28]=5.05$; $p<0.0001$]. ANOVAs also revealed two additional main effects restricted to the errors analysis. A main effect of Syllable structure emerged, $F1(1, 42)=9.03$, $p=0.005$, $\eta^2=0.18$, $F2(1, 108)=6.11$, $p=0.02$, $\eta^2=0.05$, whereas a main effect of opposition was significant, $F1(2, 84)=7.27$, $p=0.001$, $\eta^2=0.15$, $F2(2, 108)=4.26$, $p=0.02$, $\eta^2=0.07$; first, CV sounds (0.7) were better processed than CCV ones (0.9). Finally, planned comparisons demonstrated that the voicing-based opposition (1.0) induced more errors than the place-based opposition (0.8) ($F(1, 42)=9.09$, $p=0.004$) and the voicing + place-based opposition (0.7) ($F(1, 42)=13.03$, $p=0.0008$).

[2] As the Group factor has never interacted with one of the within-subject factors (as well in $F1$ as in $F2$ analyses), whether in the ‘yes’ and ‘no’ responses comparison or separately in the ‘yes’ or ‘no’ responses comparison, we did not present two-by-two ANOVAs (i.e., DY children vs. RL and then, CA controls). Nevertheless, to ensure our results, we carried out these two-by-two ANOVAs (not described in this article), which supported our conclusions.

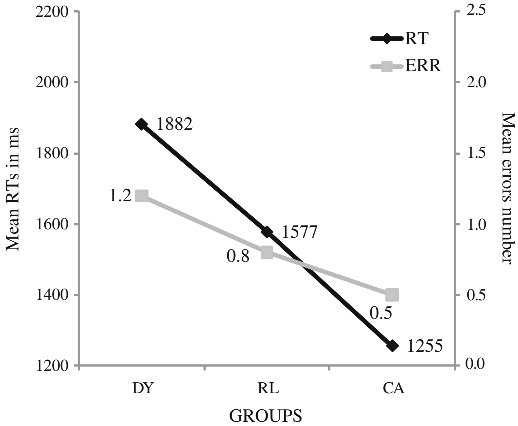

Fig. 1 Mean responses times (in milliseconds) and mean error rate (max. 6) for the 'identical' condition ('yes' responses) in RL and CA controls and DY children

Discussion

Results showed globally weaker performances in DY children compared with RL and CA controls. Similarly, RL controls exhibited weaker performances than CA controls. These results provide evidence that DY children suffered from a 'speed–accuracy' double deficit. Response times (i.e., speed) and number of errors (i.e., accuracy) were systematically impaired compared with both normal-reading groups. A posteriori analysis confirmed that mean RT and mean number of errors were correlated (identical condition, $r=0.99$; different condition, $r=0.97$). However, discrimination sensitivity threshold (i.e., d') differed between DY children and CA controls but did not between DY children and RL controls.

Interestingly, we observed a 'speed–accuracy' trade-off. Indeed, overall data revealed accuracy-based performances that distinguished the within-subject factors processing, regardless of the experimental condition. Therefore, CV syllable structures induced fewer errors than CCV syllable structures in both experimental conditions. Obstruent sounds were processed more accurately than fricative sounds within the identical condition, whereas

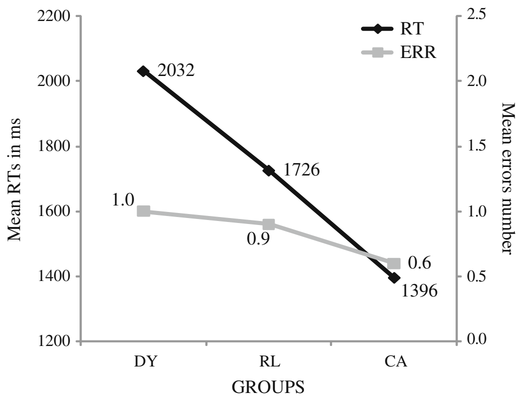

Fig. 2 Mean responses times (in milliseconds) and mean error rate (max. 4) for the 'different' condition ('no' responses) in RL and CA controls and DY children

voicing-based opposition induced more errors than the place-based opposition and the voicing + place-based opposition within the different condition.

Given these results and as we hypothesized, results in DY children—also in RL and CA controls—evidenced speed-based processing between the between-category discrimination ('different' condition) and the within-category discrimination ('identical' condition): the identical condition was processed faster than the different condition. Furthermore, children succeeded more efficiently in the discrimination of identical sounds, but failed—or labored—in the discrimination of different sounds, especially when sounds differed in a voicing-based opposition compared with a place-based opposition and a voicing + place-based opposition. As we predicted, children were affected by the minimal acoustic-phonetic variation on the first phoneme.

Surprisingly, patterns of DY children turned out to be similar to these highlighted in both normal-reading groups. The between-groups factor did not interact with within-subject factors. Thus, data clearly attested that DY children only differed from RL and CA controls in terms of 'speed–accuracy', whereas they were just as sensitive to the linguistic or acoustic phonetic characteristics as normal-reading controls. Although performances in DY children were weaker than in RL controls, we did not conclude that DY children suffered from a deviant developmental course but rather exhibited a delayed profile because of obvious shared abilities with RL and CA controls. We also proposed to test the phonological recoding procedure and the unexplored role of French linguistic characteristics in silent reading.

Experiment 2

Experiment 2 was designed to investigate whether DY children compared with CA and RL controls used phonological recoding process and how lexical and syllable frequency influenced the size of the sublexical units (e.g., phoneme or syllable) in silent reading. Our purpose was threefold. First, we predicted that children with phonological deficits would not be able to use phonological grapho-phonemic or grapho-syllabic processing. We expected a letter-by-letter serial left-to-right processing whatever the lexical or syllable frequency (i.e., a *target length effect*; that is, CV syllables would be detected faster than CVC syllables; see Colé & Sprenger-Charolles, 1999). Second, we defended the theoretical view that large-to-small progression is overstated for French. We assumed that normal-reading children follow a developmental course during learning to read from small units (i.e., phonemes) to large units (i.e., syllables) as claimed by Seymour and Duncan (1997). As evidenced in a previous study (Maïonchi-Pino et al., 2010), we hypothesized that the syllable frequency would impact the phonological processes prior to lexical frequency, as initial syllable acts as intermediate pre-lexical unit to access the mental lexicon (i.e., target × test-word × target frequency is expected). Therefore, we assumed that early and implicit auditory knowledge about syllables would help children to connect oral syllables to the frequent shape of letter groupings in larger units such as written syllables. We expected a grapho-syllabic processing (represented by a crossover interaction between Target and Test-word, which reflects a *syllable compatibility effect*) that would be influenced by syllable frequency in both groups. However, we contrasted the syllable frequency effect: as syllable-sized units are subsequently mastered to GPCs, we expected a grapho-phonemic processing with low-frequency targets (represented by a *target length effect*), but a *syllable compatibility effect* with high-frequency targets in RL controls, whereas the *syllable compatibility effect* would be extended to both target frequencies. Third, we predicted that performances would be dependent on the reading level: CA controls would outperform RL controls and DY children. However, as DY children experienced repeated oral and written exposures longer than RL controls, RL controls would underperform DY children. Similarly, we predicted lexical and syllable frequency effects in CA controls and DY children.

Participants

All of the DY, the CA children, and the RL children who were recruited in Experiment 1 also participated in this experiment. Profiles have been described in Table 1.

Method

Word reading test

The selection and classification process of the CA and the RL controls and the dyslexic children (DY) is identical to this described in Experiment 1. Profiles have been described in Table 1.

Material and design

Material and experimental design were identical as those used in Maïonchi-Pino et al.'s (2010) experiment. Twenty-four six- or seven-letter disyllabic test words whose half had an initial CV syllable structure and the other half had an initial CVC syllable structure were included. All of the test-words had the three initial letters with regular spelling-to-sound correspondences. CV and CVC test-words were subdivided into high- and low-frequency test-words. We used Manulex database (Lété et al., 2004)[3] that provides a grade-level printed word-frequency for French first-to-fifth grade readers to select six high- (μ=47) and six low-frequency (μ=3) CV test words, and six high- (μ=42) and six low-frequency (μ=1) CVC test words. Twenty-four targets whose half had a CV syllable structure and the other half had a CVC syllable structure were also included. We used Manulex-infra database (Peereman et al., 2007)[2] that supplies a printed syllable frequency in the initial position in words for French first-to-fifth grade readers to select six high- (μ=2969) and six low-frequency (μ=848) CV targets, and six high- (μ=822) and six low-frequency (μ=198) CVC targets.

Targets and test words were visually presented twice. A same target (i.e., CV or CVC) was either presented with a test word that shared the same initial syllable structure (e.g., CA with CA.RAFE 'jug' or VOL with VOL.CAN 'volcano') or that differed in the initial syllable structure (SO with SOL.DAT 'soldier' or COR with CO.RAIL 'coral'). The 'syllable compatibility' condition occurred when the target and test word matched, whereas when target and test-word did not match, we labeled it as the 'syllable incompatibility' condition. Moreover, we combined target, target frequency, test word, test word frequency factors. Half of the high-frequency CV targets was presented with high-frequency CV (i.e., 'syllable compatibility' condition) and CVC (i.e., 'syllable incompatibility' condition) test words, whereas the other half of the high-frequency CV targets was presented with low-frequency CV and CVC test words; half of the low-frequency CV targets was presented

[3] The syllable and word frequency extracted from Manulex (Lété et al., 2004) and Manulex-infra (Peereman et al., 2007) databases were the occurrences per million from first to fifth grade (i.e., U1-to-U5 column).

with low-frequency CV and CVC test words, and the other half of the low-frequency CV targets was presented with high-frequency CV and CVC test words. Similarly, half of the high-frequency CVC targets was associated with high-frequency CV and CVC test words, whereas the other half of the high-frequency CVC targets was associated with low-frequency CV and CVC test words; finally, half of the low-frequency CVC targets was associated with low-frequency CV and CVC test words, and the other half of the low-frequency CVC targets was associated with high-frequency CVC test words. Experimental conditions are exemplified in Table 5. Finally, we also controlled the oral syllable frequency (Wioland, 1985; see Appendix B for targets and test word frequency).

The design of the experiment was composed of four experimental lists. Each list contained six trials for the 'syllable compatibility' condition and six trials for the 'syllable incompatibility' condition. Overall, forty-eight experimental trials were displayed. Forty-eight distractive trials were also added and fairly distributed in each experimental list (e.g., BI with TU.LIPE 'tulip'): distractive trials have to trigger negative answers and balance the number of positive and negative answers. Response times on distractive trials were not taken into account. Children encountered all of the experimental conditions. Each experimental list was separated by a pause. The order of the presentation of the stimuli in each experimental list and the order of the presentation of each experimental list were randomized. The software automatically recorded response times and errors. The experimenter never intervened during the experiment.

Procedure

Children individually completed the task in one experimental session. The script was designed and compiled with PsyScope 1.2.5 (Cohen et al., 1993), and ran on a Macintosh iBook laptop computer. Children sat at roughly 57 cm from the screen. Printed targets and test words were displayed in police "Chicago" font, size "48". Targets and test words were systematically presented in lower case letters. Each trial consisted of the following events: a fixation cross (i.e., "+") was displayed during 800 ms in the center of the screen and was

Table 5 Sample of the experimental conditions used in Experiment 2

		CV test word		CVC test word	
		High-frequency test word	Low-frequency test word	High-frequency test word	Low-frequency test word
CV target	High-frequency target	CA CAROTTE "CARROT"	CO CORAIL "CORAL"	MA MALGRÉ "DESPITE"	CA CARBONE "CARBON"
	Low-frequency target	VO VOLANT "WHEEL"	TO TORERO "TORERO"	VO VOLCAN "VOLCANO"	TO TORNADE "TORNADO"
CVC target	High-frequency target	PAROLE PAROLE "SPEECH"	CAR CARAFE "CARAFE"	PAR PARFUM "PERFUME"	MOR MORTEL "LETHAL"
	Low-frequency target	BAL BALANCE "WAGE"	DOR DORURE "GILT"	SOL SOLDAT "SOLDIER"	PUR PURGER "PURGE"

then immediately replaced, at the same position, by a target (i.e., CV or CVC) before the test word appeared below. Target and test word remained on the screen until the child responded. The next sequence followed after a 500-ms delay. Children were instructed to decide as quickly and as accurately as possible whether the target occurred at the beginning of the test word. For right-handed preference, children had to press on ‘p’ or ‘a’ response keys, for ‘yes’—if target appeared at the beginning of the test word—and ‘no’—if not—respectively. No utterance was required: children performed silently the task. Before beginning the experimental lists, children were trained with a practice list that contained eight different trials.

Results

ANOVAs were performed on the data using subjects ($F1$) and items ($F2$) as random variables on mean RT. Only correct RT were included in the analyses. The correct RT were standardized (i.e., for each subject, the response times away from more or less two SD were replaced by the mean RT of each subject (≈4.7% of the data)). No analysis was run on errors (≈1.9% of the data). Descriptive data are summarized in Table 6.

Comparison of the three groups

A 2×2×2×2 within-subject factors (Target: CV vs. CVC; Test-word: CV vs. CVC; target frequency: high vs. low; word frequency: high vs. low) and one between-groups factor (Group: DY, RL, and CA) mixed-model ANOVA was carried out on mean RT.

The ANOVA revealed a main effect of Group, $F1(2, 42)=12.46$, $p<0.0001$, $\eta^2=0.37$, $F2(2, 96)=149.38$, $p<0.0001$, $\eta^2=0.76$. Follow-up t tests showed that DY children (1,200 ms) were significantly slower to respond than CA controls (1,034 ms) [$t[28]=5.66$, $p<0.0001$], but were faster than RL controls (1,785 ms) [$t[28]=-9.50$, $p<0.0001$]. Furthermore, RL controls were slower to respond than CA controls [$t[28]=-12.75$, $p<0.0001$]. Additionally, ANOVA highlighted a significant Group×target×test-word×target frequency interaction, $F1(2, 42)=10.66$, $p=0.002$, $\eta^2=0.20$, $F2(2, 96)=9.63$, $p=0.003$, $\eta^2=0.09$. To follow-up on this interaction, we cross-compared the target×test-word×target frequency interaction by group (i.e., DY children vs. RL and CA controls).

For the comparison of DY and RL children, the ANOVA revealed a significant main effect of Group, $F1(1, 28)=9.25$, $p=0.005$, $\eta^2=0.25$, $F2(1, 64)=113.72$, $p<0.0001$, $\eta^2=0.64$; DY children (1,200 ms) responded faster than RL controls (1,785 ms). ANOVA also revealed two additional main effects of word frequency and target frequency, $F1(1, 28)=4.10$, $p=0.05$, $\eta^2=0.13$, $F2(1, 64)=3.18$, $p=0.08$, $\eta^2=0.05$ and $F1(1, 28)=18.64$, $p=0.0002$, $\eta^2=0.40$, $F2(1, 64)=5.49$, $p=0.02$, $\eta^2=0.08$, respectively; high-frequency words (1,450 ms) and targets (1,427 ms) led to faster RT than low-frequency words (1,535 ms) and targets (1,558 ms). However, separate ANOVAs in DY children and RL controls demonstrated that main effects of word frequency and target frequency were only significant in DY children, $F1(1, 14)=8.41$, $p=0.01$, $\eta^2=0.38$, $F2<1$ and $F1(1, 14)=46.25$, $p<0.0001$, $\eta^2=0.77$, $F2(1, 32)=8.33$, $p=0.007$, $\eta^2=0.21$, respectively; high-frequency words (1,141 ms) and targets (1,089 ms) were processed faster than low-frequency words (1,259 ms) and targets (1,311 ms). ANOVA showed an overall target×test word×target frequency interaction, $F1(1, 28)=8.60$, $p=0.007$, $\eta^2=0.24$, $F2(1, 64)=8.02$, $p=0.006$, $\eta^2=0.11$. We also separately studied whether the target×test word×target frequency interaction emerged in DY children and/or in RL controls. The target×test word×target frequency interaction was only

Table 6 Statistical descriptive data in Experiment 2 (mean response times (in milliseconds), standard error (in brackets), and error rate) in RL and CA controls and DY children

		CV test word		CVC test word	
		High-frequency test word	Low-frequency test word	High-frequency test word	Low-frequency test word
RL	High-frequency CV target	1,588 (159)	1,679 (208)	1,904 (257)	1,943 (334)
		0.0%	2.2%	0.0%	0.0%
	Low-frequency CV target	1,749 (249)	1,748 (228)	1,768 (233)	1,764 (220)
		4.4%	2.2%	4.4%	4.4%
	High-frequency CVC target	1,844 (306)	2,039 (279)	1,541 (143)	1,578 (177)
		6.7%	2.2%	2.2%	0.0%
	Low-frequency CVC target	1,911 (238)	1,778 (202)	1,764 (201)	1,962 (172)
		8.9%	0.0%	4.4%	0.0%
CA	High-frequency CV target	893 (53)	917 (57)	1074 (61)	1225 (73)
		0.0%	6.7%	0.0%	6.7%
	Low-frequency CV target	1,014 (55)	966 (42)	1,146 (59)	1,285 (73)
		4.4%	2.2%	4.4%	2.2%
	High-frequency CVC target	1,070 (74)	1091 (67)	819 (47)	808 (52)
		4.4%	0.0%	6.7%	2.2%
	Low-frequency CVC target	1,098 (61)	1,150 (49)	1,025 (51)	967 (42)
		4.4%	0.0%	0.0%	0.0%
DY	High-frequency CV target	898 (40)	1,058 (62)	1,112 (69)	1,223 (82)
		0.0%	6.7%	0.0%	6.7%
	Low-frequency CV target	1,172 (72)	1,250 (69)	1,118 (57)	1,253 (72)
		0.0%	2.2%	2.2%	6.7%
	High-frequency CVC target	1,210 (94)	1,195 (96)	995 (49)	1,023 (59)
		0.0%	0.0%	2.2%	2.2%
	Low-frequency CVC target	1,265 (134)	1,446 (76)	1,358 (87)	1,627 (193)
		2.2%	4.4%	2.2%	0.0%

significant in DY children, but marginally significant in RL controls, $F1(1, 14)=6.98$, $p=0.02$, $\eta^2=0.33$, $F2<1$ and $F1(1, 14)=3.49$, $p=0.08$, $\eta^2=0.20$, $F2(1, 32)=4.54$, $p=0.04$, $\eta^2=0.12$, respectively. According to our hypotheses, we split up and analyzed the critical target×test word interaction for high- and low-frequency targets in DY children and even in RL controls (see Figs. 3 and 4). ANOVAs showed that the target×test word interaction was only significant for high-frequency targets in DY children, but marginally significant in RL controls, $F1(1, 14)=16.35$, $p=0.01$, $\eta^2=0.54$, $F2(1, 20)=13.89$, $p=0.001$, $\eta^2=0.41$ and $F1(1, 14)=3.47$, $p=0.08$, $\eta^2=0.20$, $F2(1, 20)=3.64$, $p=0.07$, $\eta^2=0.15$, respectively. Moreover, a significant main effect of target was significant for low-frequency targets in DY children, $F1(1, 14)=14.84$, $p=0.002$, $\eta^2=0.52$, $F2<1$; CV targets (1,198 ms) were processed faster than CVC targets (1,424 ms).

For the comparison of DY and CA children, the ANOVA showed a significant main effect of Group, $F1(1, 28)=13.11$, $p=0.001$, $\eta^2=0.32$, $F2(1, 64)=17.38$, $p<0.0001$, $\eta^2=0.21$; DY children (1,200 ms) responded slower than CA controls (1,034 ms). ANOVA also highlighted two additional main effects of word frequency and target frequency, $F1(1, 28)=$

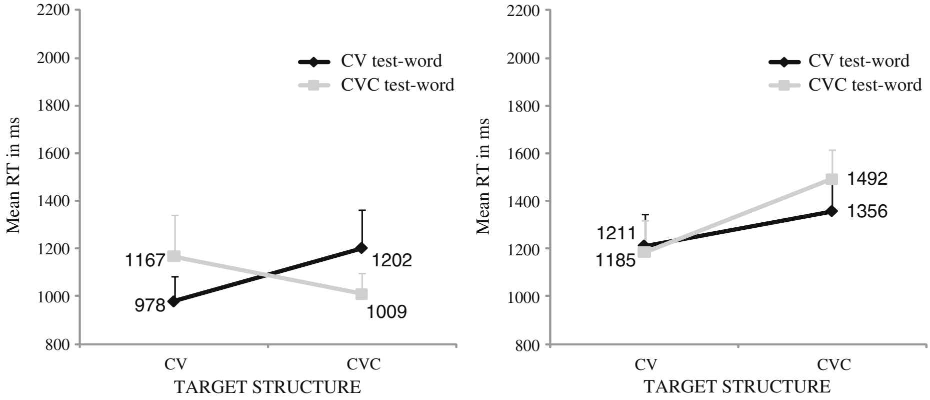

Fig. 3 Mean response times (in milliseconds) of high-frequency targets (*left panel*) and low-frequency targets (*right panel*) in DY children as a function of target structure and word structure

12.54, p=0.001, η^2=0.31, $F2(1, 64)$=3.46, p=0.07, η^2=0.05 and $F1(1, 28)$=67.69, p<0.0001, η^2=0.71, $F2(1, 64)$=16.48, p<0.0001, η^2=0.21, respectively; high-frequency words (1,079 ms) and targets (1,038 ms) were processed faster than low-frequency words (1,155 ms) and targets (1,196 ms). Separate ANOVAs for DY children and CA controls evidenced that main effects of word frequency and target frequency were significant in both DY children, $F1(1, 14)$=8.41, p=0.01, η^2=0.38, $F2$<1 and $F1(1, 14)$=46.25, p<0.0001, η^2=0.77, $F2(1, 32)$=8.33, p=0.007, η^2=0.21, respectively; high-frequency words (1,141 ms) and targets (1,089 ms) were processed faster than low-frequency words (1,259 ms) and targets (1,311 ms), and CA controls, $F1(1, 14)$=6.35, p=0.03, η^2=0.31, $F2$<1 and $F1(1, 14)$=21.57, p=0.0004, η^2=0.61, $F2(1, 32)$=19.16, p=0.0001, η^2=0.38, respectively; high-frequency words (1,017 ms) and targets (987 ms) were processed faster than low-frequency words (1,051 ms) and targets (1,081 ms). Besides, ANOVA showed an overall target×test word×target frequency interaction, $F1(1, 28)$=10.33, p=0.003, η^2=0.27, $F2(1, 64)$=5.09, p=0.03, η^2=0.07. We also separately investigated whether the target×test word×target frequency interaction popped out in DY children and/or in CA controls. Thus,

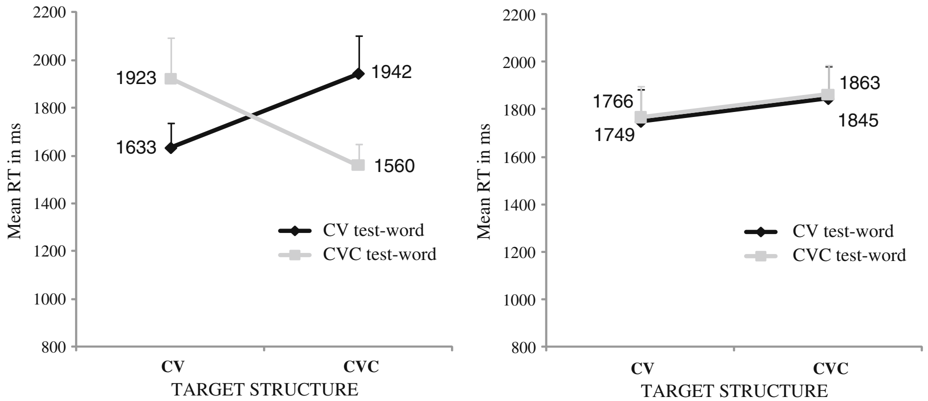

Fig. 4 Mean response times (in milliseconds) of high-frequency targets (*left panel*) and low-frequency targets (*right panel*) in RL controls as a function of target structure and word structure

the target×test word×target frequency interaction was significant in both DY children and CA controls, $F1(1, 14)=6.98$, $p=0.02$, $\eta^2=0.33$, $F2<1$ and $F1(1, 14)=4.71$, $p=0.05$, $\eta^2=0.25$, $F2(1, 32)=5.52$, $p=0.03$, $\eta^2=0.15$, respectively. According to our hypotheses, we split up and analyzed the critical target×test word interaction for high- and low-frequency targets in DY children and CA controls (see Figs. 3 and 5). ANOVAs indicated that the target×test word interaction was significant for high-frequency targets in both DY children and CA controls, $F1(1, 14)=16.35$, $p=0.01$, $\eta^2=0.54$, $F2(1, 20)=13.89$, $p=0.001$, $\eta^2=0.41$ and $F1(1, 14)=14.93$, $p=0.002$, $\eta^2=0.52$, $F2(1, 20)=48.46$, $p<0.0001$, $\eta^2=0.71$, respectively. Whereas a significant main effect of target was significant for low-frequency targets in DY children, $F1(1, 14)=14.84$, $p=0.002$, $\eta^2=0.52$, $F2<1$; CV targets (1,198 ms) were processed faster than CVC targets (1,424 ms), the target×test word was also significant for low-frequency targets in CA controls, $F1(1, 14)=11.86$, $p=0.004$, $\eta^2=0.46$, $F2(1, 20)=27.49$, $p<0.0001$, $\eta^2=0.58$.

Finally, for the comparison of RL and CA children, the ANOVA revealed a significant main effect of Group, $F1(1, 28)=15.74$, $p=0.0005$, $\eta^2=0.36$, $F2(1, 64)=353.93$, $p<0.0001$, $\eta^2=0.85$; CA controls (1,034 ms) responded faster than RL controls (1,785 ms). ANOVA only released an additional main effect of target frequency, $F1(1, 28)=5.99$, $p=0.02$, $\eta^2=0.18$, $F2(1, 64)=2.93$, $p=0.09$, $\eta^2=0.04$; high-frequency targets (1,376 ms) were processed faster than low-frequency targets (1,444 ms). Separate ANOVAs for CA and RL controls evidenced that the main effect of target frequency emerged as significant only in CA controls, $F1(1, 14)=21.57$, $p=0.0004$, $\eta^2=0.61$, $F2(1, 32)=19.16$, $p=0.0001$, $\eta^2=0.38$ as the main effect of word frequency, $F1(1, 14)=6.35$, $p=0.03$, $\eta^2=0.31$, $F2<1$; high-frequency words (1,017 ms) and targets (987 ms) were processed faster than low-frequency words (1,051 ms) and targets (1,081 ms). At last, ANOVA showed an overall target×test word×target frequency interaction, $F1(1, 28)=5.11$, $p=0.03$, $\eta^2=0.15$, $F2(1, 64)=6.27$, $p=0.02$, $\eta^2=0.09$. Again, we were interested separately in whether the target×test word×target frequency interaction emerged in CA and/or in RL controls. As previously evidenced (i.e., *DY children* vs. *RL controls* and *DY children* vs. *CA controls* subsections), the target×test word×target frequency interaction was significant in CA controls and marginally significant in RL controls, $F1(1, 14)=4.71$, $p=0.05$, $\eta^2=0.25$, $F2(1, 32)=5.52$, $p=0.03$, $\eta^2=0.15$ and $F1(1, 14)=3.49$, $p=0.08$, $\eta^2=0.20$, $F2(1, 32)=4.54$, $p=0.04$, $\eta^2=0.12$, respectively.

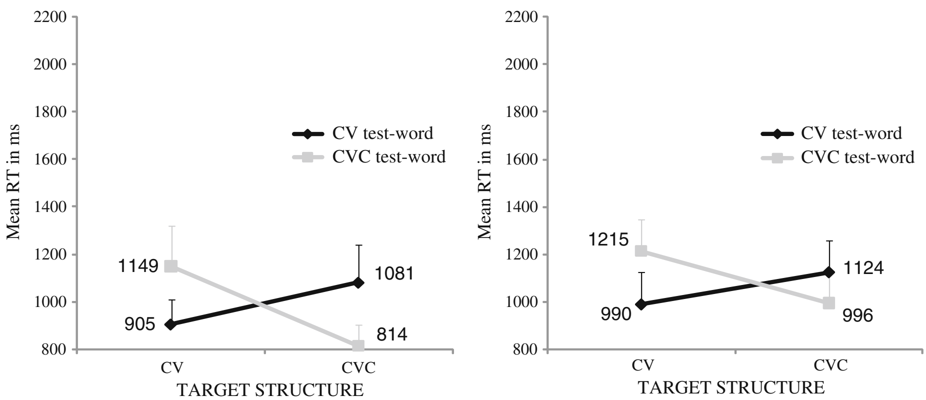

Fig. 5 Mean response times (in milliseconds) of high-frequency targets (*left panel*) and low-frequency targets (*right panel*) in CA controls as a function of target structure and word structure

Previous ANOVAs that separately considered the critical target×test word interaction as a function of high- and low-frequency targets in CA and RL controls (cf., *DY children* vs. *RL controls* and *DY children* vs. *CA controls* subsections; see Figs. 3, 4, and 5) showed that the target×test word interaction was significant for high- and low-frequency targets only in CA controls, $F1(1, 14)=14.93$, $p=0.002$, $\eta^2=0.52$, $F2(1, 20)=48.46$, $p<0.0001$, $\eta^2=0.71$, $F1(1, 14)=11.86$, $p=0.004$, $\eta^2=0.46$, $F2(1, 20)=27.49$, $p<0.0001$, $\eta^2=0.58$, respectively, and marginally significant for high-frequency targets in RL controls, $F1(1, 14)=3.47$, $p=0.08$, $\eta^2=0.20$, $F2(1, 20)=3.64$, $p=0.07$, $\eta^2=0.15$.

Discussion

Results partly corroborated those found in Experiment 1: we demonstrated that DY children underperformed CA controls but outperformed RL controls. It was also shown that reading procedures tended to be similar to those seen in both RL and CA controls. As we hypothesized, results indicated lexical and syllable frequency effects in DY children and CA controls: overall, high-frequency words and high-frequency syllables were processed faster than low-frequency words and low-frequency syllables, respectively.

However, we observed a common target×test word interaction that was primarily influenced by the target frequency, which varied as a function of the group. Results concurred with our hypotheses as the between-groups comparisons revealed that phonological procedures depended on the target frequency. High-frequency targets triggered a *syllable compatibility effect* whatever the group (marginally significant for RL controls), whereas low-frequency targets implied either a *syllable compatibility effect* (in CA controls) or a *target length effect* (in DY children), depending on children reading skills (not significant in RL controls, but from a descriptive point of view, graphics revealed a pattern close to this released in DY children). Surprisingly, DY children as well as CA controls—and marginally for RL controls—exhibited a target length effect that reflects a grapho-phonemic processing in spite of phonological deficits, and even a *syllable compatibility effect* that reflects a *higher-order* phonological grapho-syllabic processing.

Given the results, we confirmed that the lexical frequency has a minor role—no direct influence on phonological reading units—insofar as it did not interact with target and test-word unlike the syllable frequency, whatever the reading level.

General discussion

The present study was designed to investigate the status of the phonological representations in dyslexic children (DY children) compared with CA and RL controls. First, we investigated the ability for DY children to discriminate oral syllable-paired sounds in French. We assessed the implication of acoustic phonetic characteristics (i.e., voicing), mode, and place of articulation and syllable structure variations on linguistic and phonemic representations. Second, we tried to determine whether DY children were sensitive to phonological syllable-sized units in silent reading, and how French linguistic characteristics such as the initial syllable frequency and the lexical frequency could influence a contrastive use of phonological procedures.

The motivation for conducting this set of experiments was that few studies have examined the syllable's role in French DY children. Additionally, none of the past studies investigated the effect of initial syllable frequency in French DY children.

Phonological representations and categorical perception

In Experiment 1, demonstrated that discrimination thresholds were quite similar between DY children and RL controls, both lower than CA controls. We posit that lower discrimination thresholds in DY children and RL controls compared with CA controls have a different origin. In DY children, low discrimination abilities are probably due to underlying impaired phonemic representations (e.g., Bogliotti et al., 2008; Serniclaes et al., 2001; 2004). However, low discrimination threshold in RL controls might be explained because of partial phonological representations. Indeed, as proposed in French by Delahaie, Sprenger-Charolles, Serniclaes, Billard, Tichet, Pointeau et al. (2004), categorical perception abilities might depend on the reading instruction experience (see also Hazan & Barrett, 2000). Thus, as RL controls had just begun the learning to read, they might not have developed useful phonological knowledge to efficiently discriminate and categorize sounds.

On the other hand, weaker performances in DY children compared with RL and CA controls also evidenced a 'speed–accuracy' double deficit. The 'speed' deficit reflects the difficulties for DY children in accessing and processing phonological representations. The 'accuracy' deficit represents the under-specified and degraded storage of phonological representations. As suggested by Ramus and Szenkovits (2008), requirements of the task (i.e., quick and subtle variation in acoustic-phonetic sound patterns on the first phoneme) increase memory and processing load. Similarly, this result reinforces the theoretical and empirical views of Snowling (2001) who argue for speech perception disorders that result from degraded or under-specified phonological representations.

First, Experiment 1 revealed a 'speed–accuracy' trade-off. We highlighted accuracy-based responses to process within-subject factors, whereas differences between the identical and different condition underlay speed-based responses: we evidenced that 'identical' condition was responded faster than the 'different' condition.

Overall, as RL and CA controls, DY children processed obstruent sounds more efficiently than fricative ones. This result is compatible with developmental data. In French normal-developing children, Rondal (1997) showed that obstruent sounds are acquired and mastered earlier than fricative ones. Meanwhile, the prevalence of obstruent over fricative sounds normally tends to progressively disappear. For instance, Masterson et al. (1995) observed in English that fricative sounds are likely to be confused than other sounds. As DY children are considered phonologically impaired, we interpret this pattern as DY children being delayed at primary low-level representations. Contrariwise, in RL and CA controls, this difference might result from a high-sensitivity to statistical prevalence of obstruent sounds over fricative ones (see Content, Mousty, & Radeau, 1990).

Meanwhile, DY children and RL and CA controls are sensitive to the syllabic structure complexity. This supports French linguistic data showing an optimal syllable structure in terms of sonority (e.g., Clements, 1990), frequency (i.e., 76% vs. 24% of closed CVC syllables; e.g., Wioland, 1985), and universality (e.g., Clements & Keyser, 1983) for CV structure. Similarly, we reinforced previous results from Sprenger-Charolles and Siegel (1997) or Bastien-Toniazzo et al. (1999): authors demonstrated that French normally reading children preferentially reduced complex syllable structures such as CCV or CVC into a simplified and optimal CV structure. Paradoxically, we considered that DY children are potentially sensitive to coarticulation on both first phonemes in CCV structures (see Altmann, 1997, for more details) to distinguish between CV and CCV structures, whereas coarticulation might be a tedious event to be processed.

As we described, a well-defined within-category discrimination emerges in DY children as well as in RL and CA controls: children categorized two sounds as identical faster than they categorized them as different. As a general rule, this requires less constraining cognitive process to match two concordant sounds compared with two discordant sounds. More specifically, we hypothesized that DY children's preferences might be related to categorical-specific perception. In fact, we draw a parallel between better within-category discrimination (equivalent to our 'identical' condition) and weaker between-category discrimination (equivalent to our 'different' condition). A better within-category discrimination in DY children might be a specific sensitivity based on contextual acoustic cues as suggested by Serniclaes et al. (2001) or Serniclaes et al.'s (2004). If DY children are able to discriminate more efficiently allophonic variations of a same phoneme, we might expect that DY children are also able to judge more efficiently as identical two sounds belonging to the same phonemic category. However, this interpretation has to be cautiously considered: if DY children have really built phonemic categories towards contextual variations of a phoneme (i.e., allophonic speech mode of perception), we would have observed increased times of processing because the memory load would have increased to store and retrieve the unique relevant phoneme in French.

In the 'different' condition, we observed that the initial phoneme-bearing discrimination did not systematically rely on speed of processing but primarily on accuracy. The discrimination of sounds differing on a single phonetic feature such as voicing—the between-category discrimination—is a normal-reading skill (e.g., Adlard & Hazan, 1998; Serniclaes et al., 2001), especially because the voicing is a relevant phonemic variation that allows lexical discrimination. Between-category discrimination (equivalent to our 'different' condition) is usually processed by normal-reading children better than DY children (e.g., Serniclaes et al., 2001; Werker & Tees, 1987). However, DY children and CA and RL controls seem to be *negatively* affected by a voicing variation on the first phoneme: all of the children labored in the discrimination of a voicing-based opposition compared with a place-based opposition and a voicing + place-based opposition. Nevertheless, in DY children, such a result corroborates previous data collected in between-category discrimination whose deficits are due to impairments in building clearly delimited phonological categories—and phonemic representations—from an acoustic phonetic feature (e.g., Serniclaes et al., 2001), which imply difficulties to properly learn and apply GPCs (e.g., De Weirdt, 1988; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981). Contrariwise, in RL and CA controls, we believe that children did not necessarily fail to discriminate a voicing-based opposition, but as voicing is a well-defined acoustic phonetic variation, oppositions that are more distant than voicing (e.g., place-based opposition and voicing + place-based opposition) enhance discriminability.

Syllable frequency effect and phonological syllable-based processing

In Experiment 2, we showed that the task was exclusively speed-based sensitive. Thus, the more children are experienced with reading, the more RT decreases, and we believe this is why DY children reached intermediate performances between RL and CA controls. This results from multiple experiences with oral and reading exposures: we also show that some abilities have been developed in DY children in spite of phonological disorders. Besides, the difference between RL and CA controls rather suggests that phonological recoding becomes automatic to gain in processing speed. Following this interpretation, results indicated lexical and syllable frequency effects in DY children and CA controls: high-frequency words and high-frequency syllables were processed faster than low-frequency words and low-frequency syllables respectively. The GPCs teaching, and the increase of reading exposure progressively develops the orthographic lexicon, which speeds up the recognition of words frequently encountered. In DY children, syllable and lexical frequency effects underlie the development of specific abilities; through repeated oral and written exposures, DY children would have developed knowledge about regularities of French.

As we predicted, children processed targets and test words differently as a function of the target frequency (i.e., Group×target×test word×target frequency interaction) and allowed us to cross-compared DY children with RL and CA controls. More specifically, this interaction indicated that phonological procedures primarily depend on the initial syllable frequency. For all children in the study, high-frequency targets promote a *syllable compatibility effect* whatever the group, whereas low-frequency targets imply either a *syllable compatibility effect* (in CA controls) or a *target length effect* (in DY children). We also observed that the use of a phonological grapho-syllabic procedure lasts in skilled CA controls and is possible in DY children who suffer from poor phonological awareness. Surprisingly, DY children exhibit both phonological grapho-phonemic (*target length effect*) and grapho-syllabic processing. We agree that the target length effect in DY children reflect a serial left-to-right phonological grapho-phonemic processing rather than a visual serial letter-by-letter processing as far as they are *sufficiently skilled* to use a phonological grapho-syllabic processing with high-frequency targets. As all of the children were taught with a teaching method based on GPCs, we propose that children have efficiently and successfully learnt GPCs to perform the matching process. However, because phonological representations are possibly degraded and under-specified in DY children, the GPCs learning would have been more tedious than in RL and CA controls: this may explain why DY children would be slower than normally reading children. As proposed by Colé et al. (1999) or Maïonchi-Pino et al. (2010) in normally reading children, we argue that even DY children are able to sufficiently master GPCs to shift their attentional focus to associate several graphemes into larger phonological structures such as syllables, notably because a syllable-based segmentation is less constraining than a phoneme-based segmentation.

As in Maïonchi-Pino et al. (2010), we demonstrated a progressive developmental course that is based on the initial syllable frequency. Then, provided additional evidence for the hypothesis that syllable frequency influences phonological procedures prior to lexical frequency as only the syllable frequency interacted with target and test word, whatever the reading level. In fact, results turn out to be compatible with the normal developmental course proposed by Seymour and Duncan (1997), and with the experimental data evidenced by Colé et al. (1999) and Maïonchi-Pino et al. (2010). Although poor phonemic awareness and impaired phonological representations were evidenced in Experiment 1, patterns of DY children were in accordance with the resort to a phonological recoding procedure. We posit that a developmental progression occurs from a systematic phonological grapho-phonemic processing to a grapho-phonemic processing that is restricted to low-frequency targets. Implicit knowledge about oral syllables developed through multiple exposures to spoken language (e.g., Goslin & Floccia, 2007) and explicit GPCs learning strengthen the access and retrieval to syllable-sized units with high-frequency targets, before a grapho-syllabic processing is systematically applied. In line with Maïonchi-Pino et al.'s (2010) conclusions, we again demonstrated that the initial syllable frequency has no inhibitory effect. High-frequency targets did not inhibit phonological processing. Contrariwise, high-frequency targets have a facilitatory effect, namely they are processed faster than low-frequency targets and induce a phonological grapho-syllabic processing. As interpreted by Maïonchi-Pino et al. (2010), children might store high-frequency syllables they have encountered as precompiled articulatory gestures developed through the subvocal repetition and reading exposures: high-frequency phoneme associations would benefit from compiled syllabic gestures, whereas low-frequency phoneme associations would experience a systematic GPCs process. Furthermore, implicit knowledge about spoken syllables would guide the grapho-syllabic associations. Indeed, the more some spoken syllables would have been encountered, the more the written equivalent syllables would be efficiently and quickly available. Interestingly, we assume that DY children are sensitive to syllable frequency to use a phonological grapho-syllabic processing in spite of underlying degraded and under-specified phonological.

Conclusion

The results regarding the DY children were mixed. On one hand, we observed that DY children have systematically weaker performances than RL and CA controls (Experiment 1). We might assume that they did not follow a typical developmental course (i.e., deviant profile hypothesis). But, on the other hand, we showed that DY children have intermediate performances (Experiment 2) with delayed abilities similar to those developed during a normal developmental course (Experiments 1 and 2). However, DY children undergo a constant expected delay (i.e., RT) compared with CA controls and between-category discrimination deficits on voicing-based opposition of two sounds.

Surprisingly, DY children are evenly sensitive to some linguistic characteristics: syllabic structures (CV structures are preferred than CCV or CVC structures), mode of articulation (obstruent sounds are preferred than fricative ones), syllable and lexical frequency (high-frequency syllables and words are preferred than low-frequency syllables and words).

Furthermore, some of the results in DY children are counter intuitive: although they have phonological impairments, they are able to resort to phonological processing, and especially phonological grapho-syllabic processing which are influenced by the syllable frequency. We propose that DY children experienced repeated orthographic co-occurrences (e.g., Colé & Sprenger-Charolles, 1999; Doignon & Zagar, 2006), and connected implicit knowledge about spoken syllables to explicit written sequence of phonemes frequently encountered.

However, impaired performances of DY children depend on the task requirements (see Ramus & Szenkovits, 2008): Experiment 1 was temporally much more constraining than Experiment 2 as Experiment 1 involved a quick and subtle acoustic-phonetic variation discrimination, whereas Experiment 2 required a *simple* silent reading.

To conclude, results are compatible both with the hypothesis of compensated phonological representations and/or alternative under-specified phonological procedures to account for performances that are similar to those released in RL and CA controls. Meanwhile, we state that results of RL and CA controls corroborate previous results in French first, third, and fifth graders (i.e., Maïonchi-Pino et al., 2010), and may be extended to DY children to point out that the syllable is a privileged phonological reading unit whose printed frequency and complexity influence reading strategies.

As previous conclusions, we acknowledge that DY children probably present important inter-individual profile variability, and further research is required to provide an increasingly detailed framework about developmental dyslexia.

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Appendix A

Table 7 Material used in Experiment 1 for identical condition

Identical condition							
Obstruent				Fricative			
CV		CCV		CV		CCV	
Voiced	Unvoiced	Voiced	Unvoiced	Voiced	Unvoiced	Voiced	Unvoiced
bou/bou (×3)	pou/pou (×3)	brou/brou (×3)	prou/prou (×3)	vou/vou (×3)	fou/fou (×3)	vrou/vrou (×3)	frou/frou (×3)
dou/dou (×3)	tou/tou (×3)	drou/drou (×3)	trou/trou (×3)	zou/zou (×3)	sou/sou (×3)	zrou/zrou (×3)	srou/srou (×3)

Table 8 Material used in Experiment 1 for different condition

Different condition					
CV			CCV		
Voicing "V"	Place "P"	"V+P"	Voicing "V"	Place "P"	"V+P"
Obstruent					
bou–pou	bou–dou	bou–tou	brou–prou	brou–drou	brou–trou
dou–tou	dou–bou	dou–pou	drou–trou	drou–brou	drou–prou
pou–bou	pou–tou	pou–dou	prou–brou	prou–trou	prou–drou
tou–dou	tou–pou	tou–bou	trou–drou	trou–prou	trou–brou
Fricative					
fou–vou	fou–sou	fou–zou	frou–vrou	frou–srou	frou–zrou
sou–zou	sou–fou	sou–vou	srou–zrou	srou–frou	srou–vrou
vou–fou	vou–zou	vou–sou	vrou–frou	vrou–zrou	vrou–srou
zou–sou	zou–vou	zou–fou	zrou–srou	zrou–vrou	zrou–frou

Appendix B

Table 9 Material used in Experiment 2

Items structure matched by pairs and frequencies							
High-frequency test words		Low-frequency test words		High-frequency targets		Low-frequency targets	
CV and CVC		CV and CVC		CV and CVC		CV and CVC	
parole	parfum	carafe	carbone	pa	par	ba	bal
54	38	8	0	2,720	6,149	1,257	174
carotte	carton	corail	cordon	ca	car	so	sol
34	66	6	5	2,800 (×2)	1,035 (×2)	1,089	260
malade	malgré	morale	mortel	ma	mal	vo	vol
114	86	3	1	4,638	1,142	1,010	197
volant	volcan	torero	tornade	mo	mor	do	dor
19	20	0	1	3,072	436	981	328
solide	soldat	purine	purger	co	cor	to	tor
37	23	0	0	3,454	463	286	195
balance	balcon	dorure	dorsal			pu	pur
26	19	0	0			465	34

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