Tracking reading skills and reading-related skills in dyslexia before (age 5) and after (ages 10–17) diagnosis

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Abstract

This study had three goals: to examine the stability of deficits in the phonological and lexical routes in dyslexia (group study), to determine the prevalence of dyslexia profiles (multiple-case study), and to identify the prediction of phonemic segmentation and dis- crimination skills before reading acquisition on future reading level. Among a group of 373 non-readers seen at age 5, 38 students were subsequently diagnosed as either consistent dyslexic readers (18 DYS) or consistent typical readers (20 TR). Their phonological and lexical reading skills were assessed at ages 10 and 17, and their phonemic segmentation and discrimination skills at age 5. In comparison with TR of the same chronological age (CA-TR), individuals with dyslexia demonstrated an impairment of the two reading routes, especially of the phonological reading route. In the comparison with younger TR (age 10) of the same reading level (RL-TR), only a deficit of the phonological route is observed. In the multiple-case study, the comparisons with CA-TR showed a prevalence of mixed profiles and very few dissociated profiles, whereas the comparison with RL-TR resulted mostly in two profiles depending on the measure: a phonological profile when accuracy was used and a delayed profile when speed was used. In addition, the correlations between early phonemic segmentation and discrimination skills (age 5) and later reading skills (age 17) were significant, and in the group of individuals with dyslexia, early phonemic segmentation skills significantly predicted these later reading skills. Phonological reading deficits are persistent and mainly caused by early phonemic impairments.

Keywords Developmental dyslexia · Lexical reading route · Longitudinal study · Phonemic discrimination · Phonemic segmentation · Phonological reading route

Developmental dyslexia, hereafter dyslexia, is a neurodevelopmental learning disorder affecting accurate and/or fluent word reading-spelling skills despite adequate intelligence, visual or auditory acuity, and adequate educational instruction (Lyon et al., 2003). The prevalence of dyslexia has been reported to be around 5–10% among school-aged children across various languages and writing systems (Verhoeven et al., 2019). In an alphabetic writing system, the predominant etiological point of view postulates that dyslexia result from a deficit in the phonological domain (Lyon et al., 2003; Share, 2021), especially in phonemic segmentation, i.e., the ability to decompose spoken words into phonemes (often referred to as phonemic awareness). Such deficit prior to formal reading instruction would have a negative impact on the establishment, and the automation, of grapheme-phoneme correspondences.

As Goswami (2015) discussed, studies in the field of dyslexia face many methodological challenges, the main one being that of causality between potential early predictors of later reading outcomes. For example, readers with dyslexia are often compared with chronological age–matched typical readers (CA-TR), resulting in comparison with students with a higher reading level. A control group matched for reading level (RL-TR) is necessary to avoid this problem. Indeed, the observation of a significant impairment in individuals with dyslexia in comparison to RL-TR suggests a deviant development of reading skills and not a developmental delay due to a lack of written word exposition. The question of causality can also be addressed with longitudinal data in which children are followed from a time when they were still non-readers (see Castles & Coltheart, 2004).

Another question still at the core of debates on dyslexia, especially in English- and French-speaking populations (Perfetti & Harris, 2019; Sprenger-Charolles, 2019), refers to the relevance of different profiles of students with dyslexia. According to the dual-route model of reading (Coltheart et al., 2001), students with dyslexia could present either a phonological profile (i.e., difficulties primarily with the phonological reading route) or a sur- face profile (i.e., difficulties to manage to correctly memorize the visual form of the written words). The question about reliability and longitudinal stability of dyslexia subtypes would have an impact on the use and creation of adapted remediation program.

Lastly, two types of studies with competing goals have been predominant in dyslexia research: group and single-case studies. While single-case studies aim to highlight extreme profiles (representative of specific deficits), group studies aim to identify what best characterizes dyslexic behavior based on examining a large population assumed to be representative of dyslexia. Group studies neutralize individuals; thus, they do not reveal precisely how many children within the dyslexic group fit the average profile. Only multiple-case studies can be used to determine the prevalence of phonological and surface profiles and to identify the proportion of students with dyslexia who do not fall into these two categories: mixed profiles that single-case studies always neglected. Multiple-case studies use the single-case method but consider several cases not selected for their typicity, and they cover a population supposedly representative of dyslexia (Ramus et al., 2003).

To address the questions of causality and profiles in dyslexia, we thus present a group study and a multiple-case study with a longitudinal design in which individuals with dyslexia are compared to both CA-TR and RL-TR. Phonological and lexical reading skills (pseudoword, regular and irregular word reading) were assessed at age 10 and 17. In addition, phonemic skills (phonemic segmentation and discrimination) were assessed before reading acquisition (at age 5). This long-term follow-up study will allow us to determine (1) the longitudinal stability of reading deficits in students with dyslexia (group study), (2) the prevalence over time of dyslexic profiles (multiple-case study), and (3) the predictive power of phonemic skills assessed before reading acquisition, at age 5, on reading level assessed at age 17.

In our study, we expect to observe results supporting hypotheses regarding the persistence of lexical and phonological reading deficits in dyslexia (1st issue), the reliability and prevalence of subtypes (2nd issue), and the fact that phonemic skills prior to reading acquisition predict dyslexia in adolescence (3rd issue). Some of the expected outcomes are replications with French-speaking students of results obtained with English-speaking students (e.g., the Connecticut Longitudinal Study: Shaywitz et al., 1999; see also Ferrer et al., 2007; Ferrer et al., 2015). If these results are observed, they thus attest to the fact that the phonological explanation of dyslexia accounts for a range of outcomes in languages that vary in orthographic transparency, not just English (Share, 2008 and 2021).

First issue of the study: longitudinal stability of deficits in phonological and lexical reading skills (group study)

According to the dual-route model (Coltheart et al., 2001), words can be read by two read- ing routes: a phonological route based on grapheme-phoneme correspondences, needed to read unfamiliar or invented words (pseudowords), and a lexical route, required to read high-frequency irregular words. During reading acquisition, children rely first on the pho- nological reading route (in English: Waters et al., 1984; in French: Sprenger-Charolles et al., 2003), which provides a bootstrapping mechanism for reading acquisition in alpha- betic systems (Share, 1995; Ziegler et al., 2020). However, given that the phonological route is generally impaired in dyslexia and the importance of the phonological route in developing the lexical route, impairments in the lexical reading route of individuals with dyslexia are expected.

Compared with typical readers of the same CA-TR, both reading routes are often found to be impaired in students with dyslexia in languages with varying degrees of orthographic transparency (Sprenger-Charolles et al., 2011). Alternatively, when compared with typical readers matched on RL-TR, only impairments of the phonological reading route are found. For instance, studies have consistently shown a significant lexicality effect (i.e., comparison between word and pseudoword reading) among English-speaking readers with dyslexia in comparison with RL-TR (see the review by Rack et al., 1992 and the meta-analysis by Van Ijzendoorn & Bus, 1994), a result that indicates the inefficiency of their phonological reading route. In contrast, in the same comparison, the effect of regularity (i.e., the superiority of regular word reading over irregular word reading) is of the same magnitude in both groups (see the meta-analysis by Metsala et al., 1998).

Longitudinal stability of reading disabilities has been assessed in studies with children across languages with varying orthographic transparency (Greek: Psyridou et al., 2020; Finnish: Lohvansuu, et al., 2021; English: Shaywitz et al., 1999; Ferrer et al., 2015). In an English language study (Snowling et al., 1996), the short-term evolution of word-pseudoword reading was examined in comparisons between English-speaking children with dyslexia and typical readers of the same RL at the start of the study. Two years later, a progression of 15% was observed on pseudoword reading in children with dyslexia versus 42% in controls. In contrast, the differences between the groups were less marked for regular and irregular word reading, and the effect of regularity was of the same magnitude for both groups, in line with previous results (Metsala et al., 1998).

Further supports for the long-term stability of deficits were provided by the Connecticut Longitudinal Study (Shaywitz et al., 1999) in which 445 children entering public kindergarten in 1983 were separated into two main groups when they were in grade 9: 21 students who met the criteria for persistent reading disability (persistent poor readers; PPR, i.e., students with dyslexia) in grades 2 through 6 and 74 non-disabled children (35 average readers and 39 superior readers). The results from Connecticut Longitudinal Study indicated that deficits in decoding skills (i.e., the phonological reading route) were evident in PPR compared to typical readers as early as first grade and that the achievement gap between these two groups persisted into adolescence (Ferrer et al., 2007, 2015).

It remains to be examined whether these developmental trajectories are found in the long term in studies conducted in French, a language with a more consistent orthography than English (Sprenger-Charolles, 2004). To address this question, in the present study, we re-examined at age 17 two groups of children diagnosed as dyslexic or proficient readers at age 10 (Sprenger-Charolles et al., 2000). Within more transparent orthographies, such as French, past research has indicated that word reading speed should be considered when identifying students with dyslexia due to ceiling effects often associated with accuracy measures (for a review of studies with English-, French-, and Spanish-speaking children, see Sprenger-Charolles et al., 2011). For that purpose, we have adopted the use of vocal response latency measures (i.e., the time from the word's display on the computer screen to the onset of the vocal response), a measure commonly used with French adults (Martin et al., 2010) and even children (Sprenger-Charolles et al., 2000; Ziegler et al., 2008), which is more precise than reading fluency (Sprenger-Charolles et al., 2011; see also Sprenger- Charolles, 2019).

Although group studies can be used to assess the hypothesis of the existence, and longitudinal stability, of subtypes of dyslexia such as those expected in the framework of the dual-route model of reading, prevalence of these subtypes cannot be assessed and would require the use of multiple-case studies.

Second issue of the study: prevalence over time of dyslexic profiles (multiple-case study)

In the dual-route model of reading, phonological and surface dyslexia are respectively depicted as arising from a specific impairment of the phonological route (phonological profile) or of the lexical route (surface profile). In an early investigation of subtypes, Castles and Coltheart (1993) noted that, among the 53 children with dyslexia included in their study, most struggled with both irregular and pseudoword reading compared to CA-TR. However, 8 were found to have difficulties primarily on pseudoword reading (phonological profile) and 10 primarily on irregular word reading (surface profile). Castles and Coltheart concluded that irregular word reading and pseudoword reading can be developmentally dissociated. Subsequent studies (see the quantitative review by Sprenger-Charolles et al., 2011) have shown that the proportion of dissociated profiles varies according to the classification method used: classical method vs. regression-based method.

In the classical method, individuals with dyslexia (scores < 1 or 1.65 SD) are said to have a phonological profile when their phonological reading route (assessed with pseudoword reading) is primarily impaired, while surface profiles are identified when impairments in the lexical reading route are mainly observed (assessed with high-frequency irregular- word reading). When deficits are found in both routes, individuals with dyslexia are said to have a mixed profile. In contrast to the classical method, the regression method assesses a relative deficit, either in lexical reading skills relative to phonological reading skills or in phonological reading skills relative to lexical reading skills. These subtypes are defined by plotting pseudoword performance against irregular-word performance (and vice versa) and then examining the confidence intervals around the regression lines determined from the control group (90% or 95%). A phonological profile characterizes a participant who is an outlier when pseudowords are plotted against irregular words but in the normal range when irregular words are plotted against pseudowords. Surface profiles are defined in the opposite way. Individuals with dyslexia whose scores are outside the confidence intervals in both cases are said to have a mixed profile. A review by Sprenger-Charolles et al. (2011) indicated sharp differences between methods, where the classical method was found to often result in many mixed profiles, whereas the regression-based method resulted in more dissociated profiles (see also the results of Birch, 2016). However, compared to studies using the classical method, the proportionality of subtypes identified across studies using the regression method varies widely, without any clear trend within and between orthographies (see Sprenger-Charolles et al., 2011; see also the study by Birch, where few surface profiles were found and only if the regression-based method was considered). However, even if there are few dyslexics with a surface profile, it is important to take this profile into account, at least within a comorbidity perspective (Zoccolotti et al., 2021). In addition, the use of profiles could allow the implementation of specific remedial therapies as shown in the single-cases study of Law and Cupples (2017) which suggests differentiated intervention given the profile of both of their participants.

The review by Sprenger-Charolles et al., (2011; see also Sprenger-Charolles, 2019) also reveals that the proportion of dissociated profiles varies as a function of the degree of orthographic transparency (English or French) and measure (speed or accuracy) and, according to Share (2008; see also Share, 2021): "It remains to be seen to what extent the classic dual-route distinction between phonological and surface dyslexia ... relates to accuracy/speed differences, particularly in the case of more ... consistent orthographies" (p. 592). Indeed, some individuals with dyslexia may perform like average readers on nontimed measures of pseudoword reading but might show robust speed deficits. When only accuracy is considered, these students with dyslexia are incorrectly considered having unimpaired phonological reading skills. Different studies indicate that reading speed should be considered to correctly classify students with dyslexia into subtypes in transparent orthographies (e.g., in Finnish: Lohvansuu et al., 2021; in Greek: Sotiropoulos & Han- ley, 2017; in French: Ziegler et al., 2008).

Another question concerning dyslexia subtypes relates to their longitudinal stability. In some studies, high stability of the phonological profile over time was observed, while the surface profile was unstable (e.g., Manis & Bailey, 2008). In contrast, Peterson et al. (2014) found little longitudinal stability in both phonological and surface profiles using the regression-based method in a study with students followed during 5 years. These differences could be due not only to the method used for subtyping but also due to the large age range of participants (9 to 15 in Manis & Bailey, 2008; 8 to 13 in Peterson et al., 2014), which reduces the reliability of the results that emerge from these studies.

In the present study, the longitudinal stability of the subtypes is assessed in French- speaking students followed from ages 10 to 17, with very low variation in chronological age. Given the reported instability of the profiles based on the regression method, we used the classical method. The final issue of the study is to test the phonological etiology of reading deficits.

Third issue of the study: deficits in phonemic skills in dyslexia

It has been theorized that the severe and specific pseudoword reading difficulties observed in students with dyslexia stem from a cognitive deficit in the phonological domain leading to a difficulty in the processing and manipulation of oral language at the phonemic level (often assessed by a phoneme segmentation task; see Elbro & Scarborough, 2004). The ability to manipulate speech at the phoneme level is essential for the accurate and efficient mapping of graphemes to their phoneme correspondences. As a result, a child unable to attend to individual phonemes in the speech stream will experience difficulties utilizing the phonological reading route.

Research across various ages and languages has indicated that students with dyslexia suffer from deficits in phonemic segmentation, which are most often significant, even in comparison with younger children of the same RL (see the meta-analysis by Melby-Lervåg et al., 2012; see also for studies on English or French adults with dyslexia, Ramus et al., 2003, Cavalli et al., 2018). In the Connecticut Longitudinal Study, it was also observed that phonemic awareness skills (but not orthographic awareness skills) were most significant in differentiating persistent-poor readers from non-disabled readers (Shaywitz et al., 1999).

An alternative explanation for the deficit in the phonological reading route found in students with dyslexia is reduced phonemic discrimination skills. While much work has been done on the relationship between reading acquisition and phonemic segmentation, little work has been done on the impact of phonemic discrimination skills on reading acquisition (Elbro & Scarborough, 2004). Phonemic discrimination skills are assessed with tasks using, in natural speech, pairs of syllables that differ by one phonemic feature: voicing (/ do/—/to/) or place of articulation (/ba/—/da/). Research utilizing such tasks have found that phonemic discrimination skills prior to reading acquisition predict future reading skills (e.g., in French, Piquard-Kipffer & Sprenger-Charolles, 2013). However, these scores reach a ceiling level very early (around age 6), and deficits have been found in readers with dyslexia only in challenging conditions, such as a noisy environment (e.g., in French, Ziegler et al., 2009), which is often the case in classrooms.

In a recent study utilizing a test of categorical perception, Snowling et al. (2019) reported phonemic discrimination deficits in 237 English-speaking children at high risk of dyslexia. Snowling and colleagues orally presented children with a synthetic continuum that varied between /b/ and /p/. At the same time, participants were shown two pictures, one of a "bee" and one of a "pea," and were required to say if they heard "bee" or "pea" and point to the matching picture. Results indicated that early categorical perception assessed before reading acquisition (age 5 1/2) is a predictor of reading for children aged 6 1/2. A retrospective analysis found that children classified with dyslexia at age 8 had poorer categorical perception at age 5 1/2. In addition, Snowling et al. (2019) noted that phonemic discrimination significantly correlates with phonemic segmentation.

Furthermore, in a longitudinal Finnish study that followed children with a familial risk for dyslexia and typical reading controls from birth to adulthood, phonemic discrimination skills at 6 months of age and assessed using brain event-related potentials (ERPs) were found to differentiate at risk from control children and to predict reading speed until the age of 14 (Lohvansuu et al., 2021; for a review see: Leppänen et al., 2012). However, Snowling et al. (2019) noted that although sensitivity to auditory and speech stimuli in infancy measured using ERP is associated with later reading skills (Leppänen et al., 2012; Molfese, 2000), how such effects relate to typical behavioral measures of speech perception is uncertain.

Building on previous work comparing the explanatory power of phonemic segmentation and discrimination skills on later reading outcomes, the present longitudinal study assessed these two skills (with behavioral measures) prior to learning to read (at age 5) in French-speaking children who were subsequently diagnosed as either typical or readers with dyslexia at ages 10 and 17.

Overview of the current study

Three main objectives characterize this study. First, among students aged 10 and 17, the efficiency of the phonological and lexical reading routes was assessed by manipulating regularity (regular versus irregular words) and lexicality (words versus pseudowords), with measures of both accuracy and speed. Second, among students aged 17, phonemic segmentation processing speed was collected in addition to accuracy. To our knowledge, in dyslexia studies, processing speed in phonemic segmentation tasks have very rarely been measured (for some exceptions, Cavalli et al., 2018; Saksida et al., 2016). Third, among students aged 5, phonemic discrimination was assessed in addition to phonemic segmentation by a task involving yes/no responses to pairs of items differing by one phoneme (e.g., zado/zato). Some researchers (i.e., Snowling et al., 2019) have indicated that, compared to phonemic segmentation, phonemic discrimination has rarely been assessed, and the results are unclear.

For the group study (first issue), in which the efficiency of the lexical versus phonological reading routes were respectively assessed with the effects of regularity (regular words versus irregular words) and of lexicality (regular words versus pseudowords), and with two measures (accuracy and speed), our hypotheses for the CA comparisons are as follows: given that students with dyslexia are expected to have a more impaired phonological read- ing route and that the efficiency of the lexical reading route is dependent of the efficiency of the phonological reading route, these students will also show impairments in the lexical reading route. As a result, they are expected to have lower scores than CA-TR regarding their phonological (hypothesis 1a, H1a) and lexical (H1b) reading routes. However, the effect of lexicality (H1c) is expected to be more pronounced for them than for CA-TR, which is not expected for the effect of regularity (H1d). Alternatively, compared with RL-TR, two hypotheses can be stated. The first hypothesis would be that the development of word reading in individuals with dyslexia follows a deviant trajectory. In this case, only a deficit in the phonological reading route should emerge in these students (H2a). The second hypothesis would be that the development of word reading is only delayed in individuals with dyslexia. In this case, no difference between them and RL-TR should emerge, no more for the phonological process than for the lexical process (H2b).

In the multiple-case study (second issue), compared to CA-TR, most students with dyslexia are expected to present a deficit in both reading routes: mixed profiles should therefore be widespread (H3a). Alternatively, compared to RL-TR, individuals with dyslexia are expected to present either a developmental deviant trajectory or a delayed trajectory. In the case of a deviant trajectory, only a deficit in the phonological reading procedure would be identified in these students (H3b). In the case of a delayed trajectory, no difference between them and RL-TR should emerge, no more for the phonological process than for the lexical process (H3c).

About the link between phonemic skills and reading level (third issue), at age 17, students with dyslexia are expected to show phonological reading-related skills impairment and thus to have lower scores than CA-TR in the phonemic segmentation task (H4). Based on a correlational analysis, we also expect to find phonemic skills assessed before the beginning of reading acquisition (phonemic segmentation and phonemic discrimination) to correlate with the reading level assessed at age 17 (H5a and 5b) and to explain that level in regards with diagnostic groups (H5c).

Method

Participants

This study reports the follow-up from ages 10 to 17 of participants with dyslexia recruited from a cohort of 373 children who were firstly seen at age 5 (beginning of kindergarten). To be included in the study, these participants were required to be native French speakers, not from a disadvantaged background, not be literate, and have average or above average non-verbal IQ and vocabulary levels. Based on parent/guardian responses to a questionnaire, participants had no history of brain damage, language problems, psychiatric symptoms, or visual or hearing problems. They were schooled in 19 classrooms in the Parisian area, none being dedicated to children with special needs. The methods used to teach reading in the first grade in these schools, as in most French schools (Sprenger-Charolles, 2019), were a mixture of the analytical approach (focusing on simple vowels and consonants in nonsense syllables and words) and the global method (use of keywords and short texts). At age 10, among 45 below-average readers remaining from the initial cohort,[2] the reading scores of 31 children were more than two SDs below the mean on the subtest assessing fluency in text reading of a standardized test for fourth graders (ANALEC, Inizan, 1995) and thus considered children with dyslexia (see Sprenger-Charolles et al., 2000). We were able to follow up with 19 of these students at age 17. The reading scores of 18 of them were more than 1.65 SDs from those of a control group of typical readers in the Alouette test (i.e., the currently test used to screen dyslexia in France) and thus classified as individuals with dyslexia (reading time in seconds with an additional second for each non-read or misread word; mean and SD of the control group: 95.72 and 11.02; range for the 18 individuals with dyslexia: 117–249). Out of these 18 students followed up from ages 10 to 17, no more than 2 were from the same initial classrooms. It is therefore difficult to assume that there could be a strong impact of the method used to teach reading on the reading level of these students.[3]

The control group of typical readers was selected among a subgroup of 60 children from the same cohort. When they were 10 years old, 43 of the original 60 children were available for follow-up. According to their scores on the reading fluency subtest of the ANALEC, 29 were classified as average or above average readers and 14 as below average readers.

Table 1 Main characteristics of the population: chronological age, vocabulary, non-verbal IQ, and reading levels along with means, standard deviations, Student's t, and Hedge's g

	CA-TR *n* = 20 Mean (SD)	DYS *n* = 18 Mean (SD)	Student's *t*	Hedge's *g*
At age 5				
Chronological age: months	66.05 (3.33)	64.39 (2.57)	− 1.73	0.54
Non-verbal IQ (Raven): accuracy	17.70 (2.20)	16.72 (3.43)	− 1.03	0.34
Vocabulary (TVAP): accuracy	40.25 (5.69)	38.17 (6.35)	− 1.06	0.34
Pre-reading level: accuracy	2.75 (1.12)	1.56 (1.34)	** − 2.97	0.95
At age 10				
Non-verbal IQ (Raven): accuracy	32.20 (3.22)	29.28 (3.80)	* − 2.54	0.82
Reading level (ANALEC): fluency (accuracy-speed)	59.55 (10.57)	136.39 (41.86)	***7.57	2.53
Word reading level (EVALEC): errors (%)	2.60 (2.23)	10.53 (6.68)	***4.80	1.59
Vocal latencies for correct responses (ms)	729 (108)	1076 (281)	***4.92	1.63
At age 17				
Chronological age: months	199.40 (5.20)	201.94 (7.14)	1.24	0.40
Non-verbal IQ (Raven): accuracy	48.85 (4.88)	47.39 (5.10)	−0.90	0.29
Vocabulary (EVIP): accuracy	151.80 (7.96)	148.39 (11.83)	− 1.03	0.33
Reading level (Alouette): fluency (accuracy speed)	525.86 (63.26)	345.98 (62.03)	***-8.84	2.81
Word reading level (EVALEC): errors (%)	0.73 (1.40)	1.85 (2.85)	1.52	0.50
Vocal latencies for correct responses (ms)	579 (110)	692 (128)	**2.89	0.93

*$p < .05$; **$p < .01$; ***$p < .001$; Hedge's g in bold: effect size > .80

EVIP Echelle de vocabulaire en image, Dunn et al., 1993; *TVAP* Test de vocabulaire actif et passif, Deltour & Hupkens, 1980

At age 17, 21 of these 29 students with an average- or above-average-reading level were reassessed; among them, we found one below-average readers. Thus, the group of typical readers contains 20 students.

These 20 typical readers were the CA-TR group for the 18 individuals with dyslexia at age 10 and then 17.[4] In addition, the 10-year-old CA-TR group acted as a group of typical reader of the same reading level (RL-TR) than the 17-year-old dyslexic group: differences between these two groups being non-significant for word reading errors and time latencies (respectively: $t(36) = -0.91$; $p = -0.37$ and $t(36) = -0.99$; $p = -0.33$).

The main characteristics of the remaining population included in this study (18 students with dyslexia and 20 CA-TR) are presented in Table 1. As would be expected, significant differences across all literacy assessments at ages 10 and 17 were found between the CA-TR controls and the students with dyslexia, apart from word reading accuracy at age 17. Although all the children included in the cohort were at that time non-readers (i.e., not able to read a CV syllable), an unexpected group difference was observed at age 5 for the pre-reading level. This difference will be examined in the discussion.

Tasks and procedure

At ages 5 and 10, tests were administered in two sessions (lasting around 30 min) and in one session at age 17 (lasting approximately 45 min). Participants were assessed individually by trained psychologists or members of the research team. Each testing session took place in a quiet room in the schools for the 2 first sessions (5 and 10). The last testing session took place either at the adolescent's school, home, or the laboratory. For the sake of clarity, the tasks used during the 12 years of this longitudinal study are presented in Table 2.

The test scores were analyzed as raw scores to allow better detection of the between-group differences that would otherwise be smoothen by norm-referenced standard scores.

Non-verbal IQ and vocabulary

Non-verbal IQ was assessed with the Raven's Colored Progressive Matrices at the initial assessments (Raven, 1947; Raven et al., 1998) and with the Raven's Advanced Progressive Matrices at the final assessment (Raven et al., 1998).

The EVIP (Echelle de Vocabulaire en Images), a French adaptation of the PPVT-R (Peabody Picture Vocabulary Test-Revised), was administered to assess vocabulary at age 17 (Dunn et al., 1993). Participants were asked to match an orally presented word to the corresponding picture (out of 4), correct responses receiving one point. A similar test (Test de Vocabulaire Passif, TVAP, Deltour & Hupkens, 1980), standardized for ages 5 to 8, was used for the first test session: children were asked to match 30 words to the truly corresponding pictures (out of 6). Items were scored on a scale from 0 to 2 where 2 points were awarded for the choice of the correct response and 1 point for the approximate response (a "big house" for a "castle"): the maximum score was 60 points (30 item-test × 2).

Pre-reading and reading levels

The pre-reading level was assessed at age 5 by the reading of the first 10 nonsense syllables (5 with only a vowel and 5 with a consonant and a vowel, CV syllables) of a standardized reading-aloud test designed for beginning readers up to 9 years of age (BatElem, Savi- gny, 1974): only children unable to read a CV syllable were identified as non-readers and included in the cohort.

At age 10, reading time and errors were assessed using the A2 reading-aloud subtest of the ANALEC (Analyse de la compétence en lecture, Inizan, 1995), a standardized reading assessment for fourth-grade children (age 10). Participants were required to read aloud a text (~ 100 words) as rapidly and accurately as possible. The reading score was calculated based on reading time to which 5 s per error was added.

At age 17, reading level was assessed by the Alouette test (Lefavrais, 1967; see Cavalli et al., 2018). Participants were required to read aloud a text of 265 words as rapidly and accurately as possible. Reading time in seconds was used as the base score to which one second per error was added.

In addition, at ages 10 and 17, a computer-word-reading test from EVALEC (Pourcin et al., 2016; Sprenger-Charolles et al., 2005) was used to assess word reading level. This test contained 48 words (36 regular and 12 irregular) and was also used to assess the effect of regularity (see below). The scores on these tests were not used to form the diagnostic groups described in this study.

Table 2 Tasks used at the beginning (age 5), the middle (age 10), and the end (age 17) of the study

		Age of assessment		
Cognitive skill	Measure	5	10	17
Non-verbal reasoning	Accuracy	Raven's colored progressive matrices	-	Raven's advanced progressive matrices
Vocabulary	Accuracy	TVAP	-	EVIP
Pre-reading level	Accuracy	BATELEM	-	-
Reading level	Fluency (accuracy speed)	-	ANALEC	ALOUETTE
Word reading	Accuracy + vocal latencies for correct responses (ms.)	-	EVALEC	EVALEC
Pseudoword reading	Accuracy + vocal latencies for correct responses (ms.)	-	EVALEC	EVALEC
Phonemic discrimination	Accuracy (above the chance level)	EDP	-	-
Phonemic segmentation	Accuracy + response time (sec.)	First phoneme deletion (Acc)	-	First phoneme deletion (Acc and RT)

Minus sign is displayed when the skill was not assessed at a specific age

¤ Response time was assessed only at 17 years old in the phonemic segmentation task

Assessment of efficiency of lexical and phonological reading routes

At ages 10 and 17, word-pseudoword reading-aloud tests from EVALEC (Pourcin et al., 2016; Sprenger-Charolles et al., 2005) were used to assess the efficiency of lexical and phonological reading routes (see below for a description of the test items). Participants were asked to read aloud each item that appeared and remained on the computer monitor until the end of the response. They were instructed to respond as accurately and quickly as possible but not pronounce the word until they had read it completely. Practice items were used to ensure that the instructions were understood.

Responses were scored during the test session and later re-examined from digitized recordings with the EVALEC software. Vocal response latency, the delay between the appearance of the word on the screen of the computer and the onset of the vocal response, was computed using the speech signal and not a voice key because of the limitations of this methodology (see Kessler et al., 2002). This methodology allowed us to listen to the recordings and ascertain whether the responses were correct and with no false starts (including hesitations and self-corrections). Vocal response latency (calculated in milliseconds) was considered for correct responses only (see the Appendix for specifications about the EVALEC software).

These word-pseudoword reading tests from EVALEC were used to assess the effects of regularity and lexicality. The word-reading test contained 12 irregular words with either a silent grapheme ("sept"/set/) or a grapheme with an exceptional pronunciation ("e" in "femme"/fam/) and 36 regular words, 12 with a grapheme whose pronunciation is dependent on the context (the two "g" in "garage"). The items at each level matched in length (number of letters, phonemes, and syllables), bigram frequency (Content & Radeau, 1988), lexical frequency (Lété et al., 2004), and word-initial phoneme. To assess the effect of lexicalcality, we used the 36 regular words of the word reading test matched on length and ortho-graphic complexity to 36 pseudowords. To assess the effect of regularity, we used the 36 regular words and the 12 irregular words.

Phonemic skills

Phonemic discrimination was only assessed among children aged 5 by the EDP (Epreuve de discrimination phonémique; Autesserre et al., 1988). Participants were asked to make a judgment of similarity on pairs of bisyllabic words and pseudowords (CVCV or CVCVC). Non-identical pairs (18 of 36) differed according to the mode or place of articulation of the intervocalic consonant (zimé/ziné; zabo/zado). Due to the binary nature of the response (yes/no), the total number of correct responses above the chance level was used as the final score.

Phonemic segmentation was assessed in the last test session at 17 years old by a task from EVALEC (Pourcin et al., 2016; Sprenger-Charolles et al., 2005) that required the deletion of the first consonant of monosyllabic pseudowords with three phonemes: 12 CVC and 12 CCV. Participants were asked to pronounce each item after having deleted its first consonant. The number of errors plus the total time to complete each subtest was recorded for each testing time point. The task used for the first test session at 5 years old was similar, but simplest: with only 10 CV and 10 CVC pseudowords. Only the number of errors was recorded.

Results

The results are described according to the questions of the research in three sections: persistence of lexical and phonological reading skill impairments (1st issue), stability and prevalence of subtypes (2nd issue), and concurrent and earlier phonemic predictors of dyslexia (3rd issue).

First issue: persistence of deficits in phonological and lexical reading skills in dyslexia (group study)

In this section, we aimed to confirm our hypotheses on the persistence of deficits on both reading routes postulated by the dual-route model (Coltheart et al., 2001). Therefore, we first performed an analysis contrasting the scores of individuals with dyslexia and CA-TR to assess the lexicality and regularity effects in each group (chronological age comparison). A second analysis was performed contrasting the scores of individuals with dyslexia and RL-TR on the same effects to determine if the word reading developmental trajectory in individuals with dyslexia is deviant or delayed (reading level comparison).

Chronological age (CA) comparison

The results obtained for accuracy are biased by ceiling effects, especially in the older typical readers (Table 3). Due to these ceiling effects, the ANOVAs were only carried out for the latency of correct responses.

Three-way ANOVAs were conducted on latency time with group (DYS, CA) * age (10, 17 years old) * lexicality (regular word, pseudoword) or regularity (regular, irregular word). The results are presented in Table 3. For lexicality, all the main effects were significant: group ($F(1, 144)=40.52$; $p<0.001$; $\eta^2=0.20$), lexicality ($F(1, 144)=203.34$; $p<0.001$; $\eta^2 = 0.15$), and age ($F(1, 144) = 99.20$; $p < 0.001$; $\eta^2 = 0.24$). All two-way interactions were also significant: group and lexicality ($F(1, 144) = 15.87$; $p < 0.001$; $\eta^2 = 0.01$), group and age ($F(1, 144)=21.65$; $p<0.001$; $\eta^2=0.05$), and lexicality and age ($F(1, 144)=5.76$; $p < 0.05$; $\eta^2 = 0.007$). Three-way interaction was not significant ($F(1, 144) = 2.05$; $p = 0.16$).

In contrast, for regularity, only the main effects of group ($F(1, 144)=25.78$; $p<0.001$; $\eta^2=0.20$) and age ($F(1, 144)=49.93$; $p<0.001$; $\eta^2=0.25$) were significant, not the main effect of regularity ($F(1, 144) = 3.45$; $p = 0.07$). In addition, only the interaction between group and age was significant: $F(1, 144)=10.44$; $p<0.05$; $\eta^2=0.05$ (interactions between regularity and group or age, both *ps*>0.30; three-way interaction, $F(1, 144)=0.07$; $p = 0.7$).

In agreement with our hypotheses (H1a and H1b), the phonological and the lexical read- ing routes of students with dyslexia are persistently impaired, but the effect of lexicality is more pronounced for them than for the CA-TR (H1c), which is not the case for the effect of regularity (H1d).

Table 3 Chronological age comparison: errors (%) and vocal latencies for correct responses (ms) on pseudoword, regular and irregular word reading at ages 10 and 17 (Student's t and Hedge's g)

	Age	CA-TR Mean (SD)	DYS Mean (SD)	Student's *t*	Hedge's *g*
Accuracy (% errors)					
Pseudoword	10	2.08 (3.45)	17.59 (12.09)	***5.25	**1.75**
Regular words	10	1.11 (1.89)	6.02 (5.58)	**3.55	**1.18**
Irregular words	10	7.08 (7.29)	24.07 (14.26)	***4.55	**1.49**
Pseudoword	17	5.56 (4.13)	11.27 (8.96)	*2.48	**0.82**
Regular words	17	0.42 (1.02)	1.23 (2.56)	1.27	0.42
Irregular words	17	1.67 (4.36)	3.70 (5.87)	1.20	0.39
Vocal latencies for correct responses (ms)					
Pseudoword	10	939 (118)	1484 (333)	***6.58	**2.18**
Regular words	10	728 (105)	1067 (266)	***5.06	**1.67**
Irregular words	10	733 (125)	1104 (373)	***4.02	**1.33**
Pseudoword	17	739 (216)	924 (168.05)	**2.95	**0.93**
Regular words	17	576 (112)	683 (122)	**2.81	**0.90**
Irregular words	17	592 (106)	719 (156)	**2.91	**0.94**

*$p < .05$; **$p < .01$; ***$p < .001$; Hedge's *g* in bold: effect size > .80, corresponding to a large effect

Table 4 Reading level (RL) comparison: mean of error percentage and vocal latencies for correct responses (ms) on word and pseudoword reading

		RL-TR 10 Mean (SD)	DYS 17 Mean (SD)	Student's *t*	Hedge's *g*
Errors (%)	Pseudoword	2.08 (3.45)	11.27 (8.96)	***4.25	**1.35**
	Regular word	1.11 (1.89)	1.23 (2.56)	0.17	.05
	Irregular word	7.08 (7.29)	3.70 (5.87)	−1.56	.49
Vocal latencies for correct responses (ms)	Pseudoword	939 (118)	924 (168)	−0.33	.10
	Regular word	728 (105)	683 (121)	−1.24	.39
	Irregular word	733 (125)	719 (156)	−0.30	.09

*$p < .05$; **$p < .01$; ***$p < .001$; Hedge's *g* in bold: effect size > .80, corresponding to a large effect

Reading level comparison

Considering our hypotheses H2a and H2b, t-tests were used to compare 17-year-old students with dyslexia with 10-year-old RL-TR. Means and SDs are shown in Table 4. Only one comparison was significant: students with dyslexia showed a higher percentage of error compared to RL-TR only in the pseudoword reading task ($t(36)=4.25$, $p<0.001$). The group difference was not significant for pseudoword latency time ($t(36) = -0.33$; $p = 0.74$) nor for both measures on regular words (respectively for error and latency: $t(36)=0.17$, $p=0.86$ and $t(36)=-1.24$, $p=0.22$) and irregular words (respectively: $t(36)=-1.56$, $p=0.13$; $t(36)= -0.30$, $p=0.76$).

The results for response accuracy indicate that adolescents with dyslexia (age 17) perform less well than younger typical readers (age 10) only when they cannot rely on their lexical knowledge (pseudoword reading). These results support our hypothesis H2a: the developmental trajectory of word reading in individuals with dyslexia is deviant, not delayed (hypothesis H2b).

Table 5 Dyslexia profiles computed on mean of error percentage and vocal latencies for correct responses (ms) on word and pseudoword reading with both the CA and the RL comparisons (in percentages of profiles; number of individuals are displayed between parentheses

		Mixed profile	Phonological profile	Surface profile	No deficit
Chronological age comparison (CA)					
Accuracy and/or speed	10	**100% (18)**			
Only accuracy	10	**78% (14)**	11% (2)	5.5% (1)	5.5% (1)
Only speed	10	**89% (16)**	11% (2)		
Accuracy and/or speed	17	**50% (9)**	17% (3)	17% (3)	17% (3)
Only accuracy	17	17% (3)	33.3% (6)	17% (3)	33.3% (6)
Only speed	17	44% (8)	5.5% (1)	5.5% (1)	44% (8)
Reading level comparison (RL)					
Accuracy and/or speed		28% (5)	**61% (11)**		11% (2)
Accuracy only		11% (2)	**78% (14)**		11% (2)
Speed only		5.5% (1)	17% (3)	11% (2)	**67% (12)**

Bold = percentages ≥ 50%, i.e., representing the major part of the group of individuals with dyslexia

Second issue: prevalence over time of subtypes in dyslexia (multiple-case study)

The aim of the multiple-case study is to determine the specific deficits found in each dyslexic student: mainly on the phonological reading route (phonological profile), mainly on the lexical reading routes (surface profile), and in both reading route (mixed profile). The subtype profiles were based on the classical method, with 1SD below the means of the typical readers, and on accuracy and/or speed (vocal response latency) for irregular words or pseudowords. The results for the classifications (one based on CA, the other on RL) are presented in Table 5.

Comparisons with chronological age controls (CA-TR)

At the age of 10, all 18 students with dyslexia presented a mixed profile when accuracy and/or speed were considered. When only accuracy is considered, 14 with a mixed profile (78%) were identified. Among the other 4 remaining students, 2 presented a phonological profile, 1 a surface profile and 1 no deficit in irregular word or pseudoword reading. When only speed is considered, 16 students with dyslexia (89%) could be identified with a mixed profile, the other 2 presenting a phonological profile.

At age 17, only 9 of the 18 students with dyslexia were found to still present a mixed profile according to accuracy and/or speed. The other 9 were evenly distributed between the other profiles (3 in each category). When only accuracy is considered, 6 students presented a phonological profile (33.3%), 3 a surface profile, 3 a mixed profile, and the 6 remaining students had unimpaired reading skills for either irregular words or pseudowords. When only speed is considered, 8 of the 18 students with dyslexia (44%) presented a mixed profile, 2 a dissociated profile (1 phonological and 1 surface), and 8 showed no deficit.

At age 10, when compared to CA-TR, mixed profiles were prevalent in students with dyslexia regardless of the measure. At age 17, a high prevalence of mixed profiles was also observed, but only when both accuracy and speed were considered. Both results are in line with our hypothesis H3a. Therefore, we can assume that both the phonological and the lexical reading routes are impaired in the majority of individuals with dyslexia in comparison with the CA-TR.

Table 6 Phonemic skills: mean and standard deviation by groups and age plus Student's t and Hedge's g

	Age	Measure	CA-TR Mean (SD)	DYS Mean (SD)	Student's *t*	Hedge's *g*
Phonemic discrimination	5	% correct	32.66 (18.76)	19.79 (14.93)	* −2.35	.74
Phonemic segmentation	5	Error %	61.00 (29.58)	81.39 (27.48)	* −2.20	.70
Phonemic segmentation	17	Error %	5.83 (5.13)	9.95 (7.45)	1.97	.64
	17	Speed (sec)	24.00 (4.97)	31.58 (9.63)	**3.00	**0.98**

*$p < .05$; **$p < .01$; ***$p < .001$; Hedge's *g* in bold: effect size > .80, corresponding to a large effect

Comparisons with reading level control (RL-TR)

In the RL comparison, when accuracy and/or speed are considered, 11 students with dyslexia (61%) had a phonological deviant profile, 5 a mixed profile, and 2 no deficit at the word level, whereas surface profile has disappeared. When only accuracy is considered, 14 students with dyslexia were found to have a phonological profile (78%), 2 mixed profile, and 2 unimpaired skills in either irregular word or pseudoword reading. When only speed is considered, 12 students (67%) had no reading deficit, 3 presented a deviant phonological profile, 2 a surface profile, and 1 a mixed profile.

In comparison with the younger RL-TR, 17-year-old students with dyslexia presented one of two main profiles: a "deviant" profile with a specific deficit of the phonological reading route when accuracy alone is considered (in line with H3b) and a "delayed" profile without deficits of the phonological or lexical reading routes, when speed only is considered (in line with H3c).

Third issue: persistence of phonemic deficits before (age 5) and after (age 17) reading acquisition and long-term prediction of reading level

The analyses conducted in this part are aiming to determine if deficits in phonemic skills are already present before reading acquisition in individuals with dyslexia and if these deficits persist up to age 17. A correlational analysis will be performed to identify the link between pre-reading phonemic skills and reading level at age 17.

Persistence of phonemic deficits at ages 5 and 17

At age 5, group differences were observed for both phonemic segmentation and phonemic discrimination tasks (respectively: $t(36)=2.20$, $p<0.05$ and $t(36)=2.35$, $p<0.05$, see Table 6) and also in pre-reading skills ($t(36) = 2.97$, $p < 0.01$; see Table 1).

Table 7 Correlations between reading skills in students aged 17 (Alouette) and predictors at age 5

	Age 17: Reading level (Alouette)	Age 5: Pre-reading level[a]	Age 5: Phonemic discrimination
Age 5: Pre-reading level	** 0.50		
Age 5: Phonemic discrimination	* 0.39	** 0.48	
Age 5: Phonemic segmentation (errors)	** −0.44	* −0.38	** −0.58

[a]Grapheme-phoneme correspondences for vowels; *$p < .05$; **$p < .01$; ***$p < .001$

At age 17, phonemic segmentation skills were assessed using two measures: accuracy (error percentage) and processing time (see Table 6). Group differences were only significant for processing time ($t(36)=3.00$, $p<0.01$). However, the difference for accuracy, although not significant ($t(36)=1.97$, $p=0.06$), was moderate in magnitude ($g=0.64$) and should therefore not be overlooked. These results corroborate the hypothesis postulating that individuals with dyslexia demonstrate a persistent impairment in phonological segmentation skills compared to CA-TR (H4).

Relations between early phonemic skills (age 5) with later reading level (age 17)

The two phonemic measures collected at age 5 were significantly correlated with reading level at age 17 (see Table 7): phonemic segmentation ($r = -0.44$, $p < 0.05$) and phonemic discrimination ($r=0.39$, $p<0.05$). These results agree with our hypotheses which postulated links between phonemic discrimination, phonemic segmentation, and future reading level (H5a and 5b). Significant correlations were also found between the two phonemic skills ($r=-0.58$, $p<0.001$) and between pre-reading level and future reading level ($r=0.50$, $p<0.01$).

In addition, the correlation between pre-reading level (at age 5) and reading level at age 17 (see Table 7) was significant ($r=0.50$, $p<0.01$) as well as the correlations between that measure and the two phonemic measures collected at age 5: for phonemic segmentation ($r = -0.38$, $p < 0.05$) or phonemic discrimination ($r = -0.48$, $p < 0.05$).

Given the relatively small number of participants, a multiple regression analysis with only phonemic segmentation and the interaction with group was conducted to explain the reading level assessed at age 17. The model showed an adjusted R^2 of 0.67 ($F(2, 35)=38.83$, $p<0.001$). Phonemic segmentation at age 5 did not directly predict reading level at age 17 ($t=0.48$, $p=0.63$, $\beta=0.06$). However, the interaction between phonemic segmentation and group (see Fig. 1) was significant ($t=-7.47$, $p<0.001$, $\beta=-0.86$) and explained by a stronger effect in the dyslexic group: correlation coefficient in the dyslexic group ($r = -0.47$, $p < 0.05$) compared to typical reader group ($r = -0.13$, $p = 0.59$).

These last results confirm the hypothesis on the long-term effect of pre-reading phonemic segmentation skills on reading level at the end of adolescence in individuals with dyslexia (H5c).

Discussion

This long-term longitudinal study shows consistent results supporting hypotheses regarding (1) the persistence of lexical and phonological reading deficits in dyslexia, (2) the reliability and prevalence of subtypes, and (3) earlier phonemic predictors of dyslexia in ado lescence. Some of the observed effects are replications with French-speaking students of results obtained with English-speaking students, in agreement with the fact that the classic dual-route model accounts for a range of outcomes across languages varying in orthography transparency, not just English (Share, 2008 and 2021). Others are new.

Persistence of deficits in phonological and lexical reading skills in dyslexia

One of the main findings of this study is the very high stability of the two groups of readers: from 10 to 17 years of age 90.5% of the participants remain in the same group (20 of the 21 typical readers and 18 of the 21 individuals with dyslexia, the reading level of the 4 excluded students being between 1 and 1.65 SD of the norms). These findings replicate those of studies in which high stability in groups of typical and readers with dyslexia is observed until the end of secondary school (in English: Shaywitz et al., 1999; Ferrer et al., 2007 and 2015; in Finnish: Lohvansuu et al., 2021).

Regarding our specific hypotheses, compared with the same CA-TR, it was not possible to use accuracy scores due to ceiling effects in 17-year-old typical readers. For vocal latency times, in accordance with hypotheses H1a and H1b, students with dyslexia pre- sent a deficit in both reading routes. However, as expected, the effect of lexicality is more noticeable in them than in typical readers (H1c), but not the effect of regularity (H1d).

For the comparison between adolescents with dyslexia (age 17) and younger RL-TR (age 10), it was possible to use both accuracy and speed. Only one significant group difference is observed: students with dyslexia produce more errors in pseudoword reading than RL-TR. This result reproduces those reported in reviews and meta-analyses with English students (Metsala et al., 1998; Perfetti & Harris, 2019; Van Ijzendoorn & Bus, 1994). In addition, the manifestation of this deficit depends on the age of the students with dyslexia and how it is measured: it is found based on accuracy scores with young French-speaking children (as in Sprenger-Charolles et al., 2009) and based on speed with French-speaking adolescents or adults (as in Martin et al., 2010).

Prevalence over time of subtypes in dyslexia

Compared to CA-TR, as predicted by hypothesis H3a, there is a prevalence of mixed pro- files among readers with dyslexia with variations by age and measures. The results are very clear for children with dyslexia (age 10): 100% for either accuracy or speed, 78% for accuracy only, and 89% for speed only. They are less clear 7 years later (age 17): 50% for either accuracy or speed, 17% for accuracy only, and 44% for speed only. Nevertheless, the percentage of dissociated profiles is very low, especially the surface type: a maximum of 6 participants with a phonological profile and a maximum of 3 with a surface profile. Importantly, based only on accuracy, 6 adolescents with dyslexia behave like CA-TR and 8 when only speed is considered. These results show the need to consider both accuracy and speed in dyslexia assessments with adolescents and adults.

The comparison with younger RL-TR (age 10) with the same reading-age that students with dyslexia (age 17) show one of the two expected profiles depending on the measure used: when only accuracy is considered, a “deviant” phonological profile (characterized by a strong and selective deficit in pseudoword reading), which is consistent with H3b; when only speed is considered, a “delayed” profile (they behave like younger typical readers), consistent with H3c.

The differences with the results of English studies that reported a larger percentage of dissociated profiles (e.g., Castles & Coltheart, 1993; Manis & Bailey, 2008; Peterson et al., 2014) could be not only due to the depth of the English orthography, but also to the method used (see: Birch, 2016; Sprenger-Charolles et al., 2011). In addition, the presence of large range in participants age reduce the reliability of the results that emerge from some English studies (81/2 to 15 in Castles & Coltheart, 1993; 9 to 15 in Manis & Bailey, 2008: 8 to 13 years in Peterson et al., 2014). The choice to mix students with such wide age gaps is challenged by the differences observed in the comparisons between individuals with dyslexia and CA-TR vs. RL-TR through reading acquisition and our study. In addition, that choice is not compatible with most of the developmentally plausible learning mechanisms accounting for typical and atypical reading acquisition in alphabetic orthographies (see hereafter our provisional explanation). To conclude, we have demonstrated in this study the instability, between the ages of 10 and 17, of dissociated profiles, and especially of the sur- face type (see also Sprenger-Charolles et al., 2011, and Sprenger-Charolles, 2019). There- fore, it seems unwise to propose differentiated interventions based on this type of profile, except in exceptional cases.

Phonemic skills and earlier predictors of dyslexia in adolescence

Phonemic segmentation skills and reading level (age 17)

Regarding the results of the oldest students (age 17) in the phonemic segmentation task, a significant group difference is found for processing time, but not for accuracy. In line with hypothesis 4, the first result highlights the need to consider both accuracy and speed to diagnose dyslexia in tasks assessing phonemic segmentation skills.

Early phonemic segmentation predictor (age 5) of reading level (age 17)

As indicated by a meta-analysis (Melby-Lervåg et al., 2012), early phonemic segmentation skills are robust predictors of future reading skills in an alphabetic system. However, some researchers postulate that when pre-reading skills are considered, the contribution of these phonemic skills to future reading level is no longer significant (Castles & Coltheart, 2004), a point of view consistent with the assumption that the ability to segment words into phonemes is a mere consequence of reading acquisition in an alphabetic system (Morais et al., 1986).

In the present study, the correlation between early phonemic segmentation (assessed at age 5) and the future reading level (assessed at age 17) is significant (0.44). In addition, the multiple linear analysis indicates a stronger effect in the group of readers with dyslexia compared to the group of typical readers of previous phonemic segmentation skills on the future reading level. Children's pre-reading levels cannot explain these results. Indeed, those selected at age 5 were all non-readers (i.e., unable to read one of the five CV syllables included in the pre-reading test). However, some of them could read some of the 5 vowels included in this pre-reading test, and the difference between children with a future diagnosis of dyslexia and future typical readers was significant (Hedge's $g = -0.95$).

These results reproduce earlier observations from a French longitudinal study that included 5-year-old children selected with the same pre-reading test (Piquard-Kipffer & Sprenger-Charolles, 2013): the recognition of at least one of the five vowels included in that test uniquely and significantly contributes to explaining variance in reading levels 3 years later. These results, which differ from those reported in English where children have specific difficulties learning the name and the sounds of vowel letters (Stuart & Colt- heart, 1988), can be explained by the fact that in French, vowel names and vowel sounds most often coincide. It is the case for the five vowels included in the pre-reading tests used in these two studies ("i," "o," "u," "é," and "ou"). In English, however, these vowels (as well as all English vowels) can have many pronunciations (see Delattre, 1965). In addition, most studies do not distinguish letter sound (or letter-name) for vowels vs. consonants (e.g., Clayton & Hulme, 2018; Kim et al., 2021).

Another interpretation of these results is possible: a deficit in the formation and integration of graphemes (visual units) to phonemes (phonological units). Such deficit could explain the reading difficulties of students with dyslexia, independently of their phonological impairment (Blomert & Willems, 2010). Indeed, in the French pre-reading task, the children must link a visual target (a letter representing a vowel) to a phonological target (the sound of a vowel). The results of the present study indicate that 1 year before the beginning of formal reading acquisition, the scores of the children with a future diagnosis of dyslexia were lower than those of the future typical readers not only in this pre-reading task with vowels, but also in the two phonemic tasks (discrimination and segmentation). In addition, significant correlations are found between these three tasks, all being also significantly correlated with the reading level at age 17. These results differed from those of Blomert and Willems (2010), who found no relationship between kindergarten phonological processing deficits (including in phonological awareness tasks) and first-grade reading deficits. The results of Blomert and Willems (2010), although contrary to previous research, assert that only learning to associate and integrate letters and speech sounds appears to be directly related to the development of a reading deficit.

Early phonemic discrimination predictor (age 5) of reading level (age 17)

The results of the current study reproduce in the long term some earlier observations from a French short-term longitudinal study that also supports the view that early phonemic dis- crimination skills are also significant predictors of future reading skills (Piquard-Kipffer & Sprenger-Charolles, 2013). In that study, children identified at age 5 as at-risk, or not, for future reading difficulties (given their phonemic discrimination scores) demonstrated lower reading level at age 8 compared to the non-at-risk group; and according to the results of a discriminant analysis based on their risk status at 5 years old (i.e., at-risk or non-at-risk), 71% of the children were correctly classified as typical or poor readers at 8 years of age.

Our results also replicate and reinforce those of the study by Snowling et al. (2019) in which phonemic segmentation and phonemic discrimination are assessed before reading acquisition (age 5 1/2) in 237 English children at high risk for dyslexia. Longitudinal relationships indicate that (1) early phonemic discrimination skills, which correlates with phonemic segmentation skills, predict the future reading level of children (at age 6 1/2), and (2) children classified as readers with dyslexia at age 8 have poorer phonemic discrimination skills at age 5 1/2.

Provisional explanations

Newborns perceive different phonemic oppositions that can be used in any world language. Gradually, in the first year of a child's life, this repertoire will be restricted to the phonemic categories necessary to process their mother tongue (Kuhl, 2004). That development, which involves a process of selection of the phonemic categories not required to process their own language, may not have been well achieved in children with a future diagnosis of dyslexia and therefore might explain the difficulties they encounter making grapheme-phoneme correspondences, a procedure that needs well-established phonemic representations.

In addition to studies assessing phonemic discrimination skills with natural speech, those assessing similar skills with synthetic speech have also shown that readers with dyslexia have lower phonemic discrimination skills than typical readers of the same CA (in English: Joanisse et al., 2000; in French: Bogliotti et al., 2008; Serniclaes et al., 2001) or RL-TR (Bogliotti et al., 2008). However, a deficit in phonemic discrimination is not found in other studies, especially those that considered adults and when accuracy only is examined (in English: Hazan et al., 2009; in French: Ruff et al., 2001; Ruff et al., 2002). Nevertheless, differences that do not appear in some of these studies for accuracy are manifested either in processing speed (Ruff et al., 2001) or in neurological correlates (Ruff et al., 2002; Virtala et al., 2020).

Deficits in phonemic discrimination, combined with those in phonemic segmentation, would negatively impact the establishment of the phonological reading route (based on grapheme-phoneme correspondences), a deficit which, given the key role of this reading route in the establishment of the lexical route (self-teaching mechanism: Share, 1998; Ziegler et al., 2020), would also negatively impact the establishment of the lexical reading route.

These results allow us to better understand the causal chain that may explain the deficit in the automation of the two reading procedures in dyslexia. Further long-term longitudinal studies are needed to give these new phonological interpretation solid empirical bases in different languages with a more or less deep orthography.

Concluding remarks

The results of the current study also have practical implications for teachers and speech therapists. Evaluation of both phonemic discrimination and phonemic segmentation skills should be part of a diagnosis of dyslexia. These evaluations should consider accuracy and speed, at least in older students. And because accuracy rapidly reaches a ceiling in word reading tasks, speed should also be assessed, and with fine-grained measures such as vocal response latencies computed for each word using the speech signal and not a voice key because of the limitations of this methodology (Kessler et al., 2002). With that methodology, it is also possible to listen to the recordings and ascertain whether the responses were indeed correct and with no false starts (including hesitations and self-corrections). That methodology, one of the few that allows to correctly identify the progressive automation of the two reading routes, and thus to adequately diagnose dyslexia, has been applied to EVA- LEC, a French tool designed to help speech therapists to diagnose dyslexia.[5]

The current study, one of the few with a long-term longitudinal design (ages 5 to 17), involves a small number of students (18 individuals with dyslexia and 20 typical readers) as other studies with participants presenting dyslexia: 9 students with dyslexia in Sotiropoulos and Hanley (2017), 16 adults with dyslexia in Ramus et al. (2003), 17 in Hazan et al. (2009), and 21 individuals with persistent reading difficulties in the Connecticut Longitudinal study (Shaywitz et al., 1999). It should be underlined, that, to collect data on 20 children with dyslexia over a long-term period (as in the present study and in the Connecticut Longitudinal study), 300 to 400 children must be examined at least two times.

Appendix.

Clarification on the semi-automatic system used to calculate the duration of vocal responses

Voice keys, usually proposed to detect the onset of a vocal response, are triggered from a single amplitude threshold, so that various spurious noises can interfere with the measurement. To circumvent this problem, we used a program to visualize and listen to the speech signal (see Fig. 2)2), in addition to a semi-automatic detection program (see Figs. 3 and 4), developed under the direction of René Carré (CNRS and France-telecom, now honorary senior researcher).

Figure 1 – 4

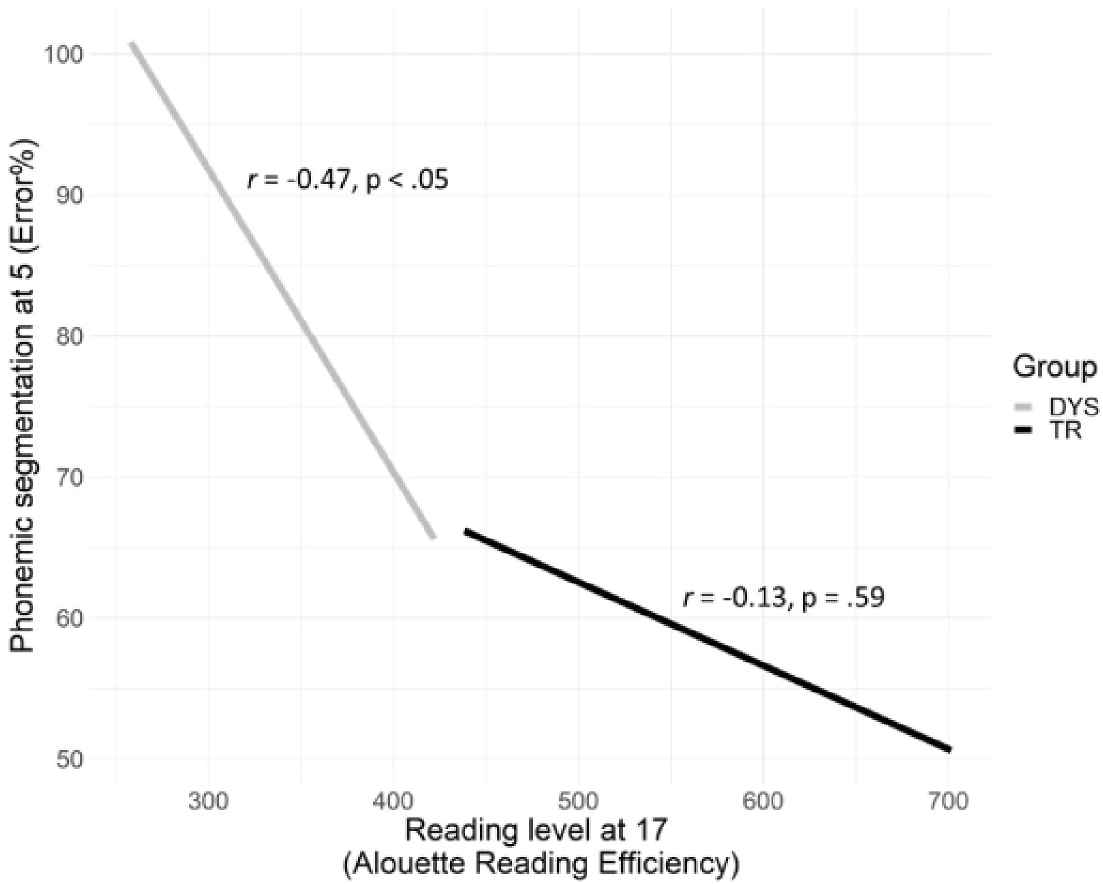

Fig. 1 Prediction interaction of the reading level at 17 years old by the phonemic segmentation score at 5 years old given groups. Left (in gray), students with dyslexia; right, (in black) CA-TR

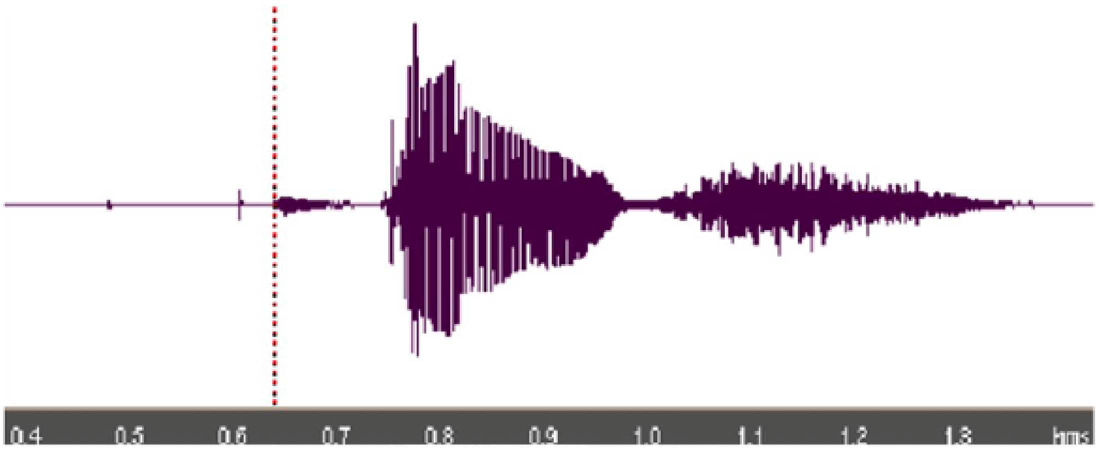

Fig. 2 Example of the visualization of a speech signal, here the word "dance". The red line corresponds to the real beginning of the word

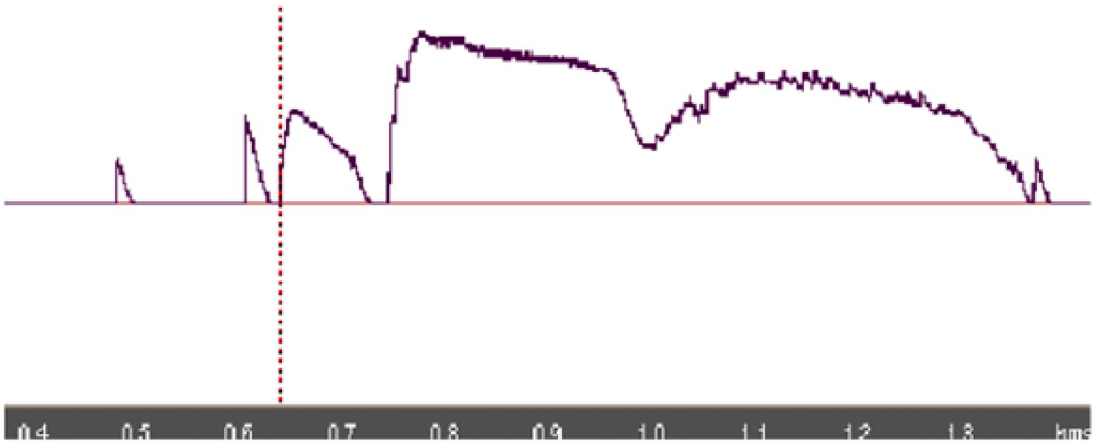

Fig. 3 The speech signal of the word dance after the first smoothing procedure with the 10 ms time constant. The red line corresponds to the real beginning of the word

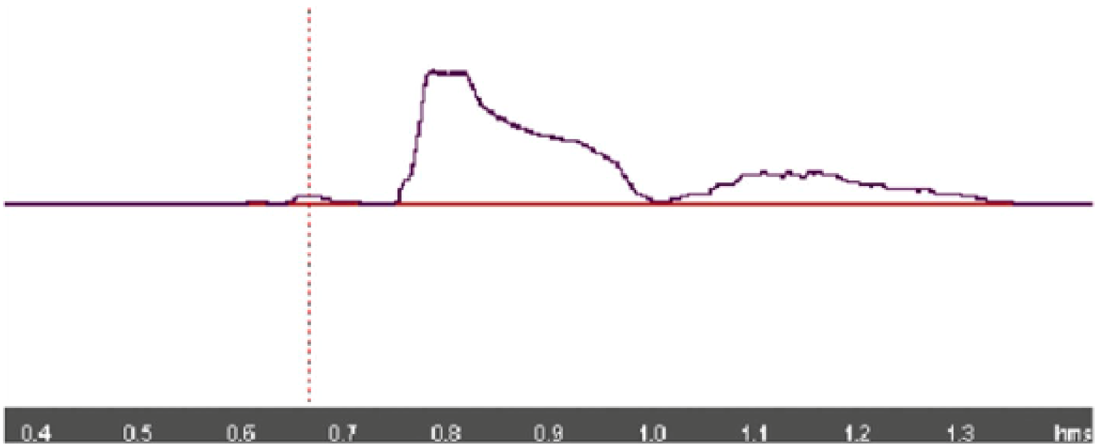

Fig. 4 The speech signal of the word dance after the second smoothing procedure with the 50 ms constant in addition to the first smoothing procedure. The red line corresponds to the real beginning of the word

Figure 2 gives the example of the speech signal corresponding to the word "dance": the real beginning of that word (considering the pre-voicing of the plosive /d/), is located at 635 ms (cf. the red vertical dotted line), two spurious noises are found before this mark.

The semi-automatic detection program exploits the energy characteristics of the recorded signal which, after calculation, is smoothed with a first-time constant of 10 ms. A new smoothing is then carried out, with a time constant of 50 ms, which makes it possible to eliminate short-lived interference and to obtain (by thresholding) an evaluation of the position of the beginning of the signal. From this value, the signal is scanned backwards to detect its beginning with a better accuracy.

Figure 3, which represents the energy (dB) after the two successive smoothing procedures, shows that the spurious noise has almost disappeared. Figure 3 represents the energy (dB) smoothed with the first time constant of 10 ms. On this curve, looking upstream from the previous dotted line, we find the beginning of the energy rise and obtain a starting point at 635 ms, which corresponds to the beginning of the speech signal represented in Fig. 2. The 2 peaks preceding this mark (spurious noise) are not considered.

After running the program, we found that, if the useful signal is framed by a sufficiently large time window, the detection of the beginning of the signal is very reliable (less than 1/100th of the real time, after verification by listening). However, some interfering noises (coughing, hesitations...) cannot be easily eliminated by the developed procedure, so it is always necessary to visualize and listen to the original vocal signal (Fig. 2).

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Declarations

Ethics statement This work was performed within the framework of the LABEX CORTEX (ANR-11-LABX-0042) of Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR). The parents (or guardians) of each student involved in the study provided their written consent.

Conflict of interest The authors declare no competing interests.

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