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Phonological syllables allow children with developmental dyslexia to access words

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Abstract

Learning to read is a middle-distance race for children worldwide. Most of them succeed in this acquisition with “normal” difficulties that ensue from the progressive (re)structuring of the phonological and orthographic systems. Evidence accumulated on reading difficulties in children with developmental dyslexia (DYS children, henceforth) shows a pervasive phonological deficit. However, the phonological deficit may not be due to degraded phonological representations but rather due to impaired access to them. This study focused on how and to what extent phonological syllables, which are essential reading units in French, were accessible to *DYS* children to segment and access words. We tested the assumption that *DYS* children did not strictly have pervasive degraded phonological representations but also have impaired access to phonological and orthographic representations. We administered a visually adapted word-spotting paradigm, engaging both sublexical processing and lexical access, with French native-speaking *DYS* children ($N = 25$; $M_{\text{age in months}} = 121.6$, $SD = 3.0$) compared with chronological age-matched peers ($N = 25$; $M_{\text{age in months}} = 121.8$, $SD = 2.7$; *CA* peers henceforth) and reading level-matched peers ($N = 25$; $M_{\text{age in months}} = 94.0$, $SD = 4.6$; *RL* peers henceforth). Although *DYS* children were slower and less accurate than *CA* and *RL* peers, we found that they used phonological syllables to access and segment words. However, they exhibit neither the classical inhibitory syllable frequency effect nor the lexical frequency effect, which is generally observed in typically developing children. Surprisingly, *DYS* children did not show strictly degraded phonological representations because they demonstrated phonological syllable-based segmentation abilities, particularly with high-frequency syllables. Their difficulties are rather interpreted in terms of impaired access to orthographic and phonological representations, which could be a direct effect of difficulties in generalizing and consolidating low-frequency syllables. We discuss these results regarding reading acquisition and the specificities of the French linguistic system.

Keywords

Dyslexia; Phonological deficit; Reading; Syllable; French; Word-spotting paradigm

Introduction

Learning to read is a crucial milestone in a child's socio-cognitive development. Although this is undoubtedly effortful, many children fail to acquire normal reading skills. Across the world, the proportion of school-aged children with developmental dyslexia, a common neurobehavioral disorder, varies from 3-to-15% (Lyon et al., 2003). Developmental dyslexia is a genetic neurodevelopmental disorder that is primarily defined as an impaired acquisition of reading skills despite normal intellectual, psychological, social, or educational factors (Doust et al., 2022; Grigorenko et al., 2020; Vellutino et al., 2004). To date, cross-linguistic studies have suggested that the most representative cognitive disorder lies in a phonological deficit, which tends to be a *universal* marker of reading difficulties (Caravolas et al., 2013; Goswami et al., 2011; Landerl et al., 2013; Saksida et al., 2016; Ziegler et al., 2008, 2010; but see Share, 2021).

Sources of the phonological deficit

Over the past two decades, researchers have faced fierce debate on theoretical frameworks that account for difficulties in developmental dyslexia. Indeed, the nature of the phonological deficit is unclear. This has led to a confrontation between the *degraded/under-specified (or over-specified) phonological representation hypothesis* and the *phonological access hypothesis*. The degraded/under-specified (or over-specified; i.e., allophonic mode of speech perception which preserves distinction between sounds even if these sounds are not represented in the language-specific inventory of sounds and, hence, overwhelm the phoneme representations to make the grapheme-to-phoneme correspondences – GPCs henceforth – misleading and confusing; Serniclaes et al., 2004) phonological representation hypothesis views the phonological deficit as a categorical perception deficit that implicitly impacts the robustness and distinctiveness between the phonological units that are essential to converge phonological and orthographic representations (i.e., GPCs; Castles et al., 2018; Snowling, 2001; Ziegler et al., 2014; for a review, see Snowling et al., 2020). According to this hypothesis, DYS children experience difficulties in identifying and/or discriminating sounds that differ in a brief and single acoustic-phonetic transition (i.e., voicing; e.g., /ba/ vs. /pa/) to account for their misuse of the appropriate reading units (for a review, see Noordenbos & Serniclaes, 2015; for alternative arguments that dissociate the phonological deficit from the acoustic-phonetic deficit, see Berent et al., 2022). An extension of the degraded/under-specified (or over-specified) phonological representations hypothesis relies on disabilities to automatically extract and tune to sound regularities to form a *perceptual anchor* in working memory, which is supposed to be a critical landmark to quickly and efficiently re-access sounds and sound sequences that have been previously encountered (Ahissar, 2007). This hypothesis corroborates previous works that suggest the phonological deficit in DYS children and adults to result from difficulties in learning statistical distribution of sounds. As a result, this leads to failure in memorizing, and subsequently storing and accessing, phonological representations, in particular the phonemes, to establish the GPCs (Gabay et al., 2015; Saffran, 2018; Vandermosten et al., 2019).

The alternative phonological access hypothesis (Ramus & Szenkovits, 2008) claims that the phonological deficit would stem from difficulties in memorizing, accessing, and retrieving the phonological representations in contexts that impose specific perceptual and cognitive demands in DYS adults (i.e., speed, noise, etc.; Mengisidou & Marshall, 2019). Of interest, some neurocognitive evidence supports the phonological access hypothesis in DYS adults (e.g., Boets et al., 2013) whereas the others support degraded/under-specified (or over-specified) phonological representation hypothesis in DYS children which is, however, insufficient to account for their reading disabilities (Boets, 2014; Vandermosten et al., 2020). This comes from studies in which DYS children exhibit intact phonological abilities, either in the use of phonological units or in the use of statistical regularities, across different tasks, even in a few tasks expected to highlight a phonological deficit in DYS children or adults (i.e., *phonological grammar*; Berent et al., 2012, 2013, 2016; Maïonchi-Pino et al., 2012, 2013; Marshall et al., 2010; Ramus & Ahissar, 2012; Soroli et al., 2010; Szenkovits et al., 2016; Szenkovits & Ramus, 2005).

Here, the matter is not to question the existence of a phonological deficit in developmental dyslexia but rather to understand its expression. Converging phonological and orthographic representations is challenging, particularly in opaque orthographies that slow down reading acquisition and exacerbate reading difficulties (Landerl et al., 2013; Sprenger-Charolles et al., 2011). Indeed, this connection emerges earlier and faster in languages with regular spelling-to-sound and/or sound-to-spelling

correspondences (Seymour et al., 2003). Segmenting phonological representations into smaller units (syllables → phonemes) or assembling them into larger ones (phonemes → syllables) requires children to successfully restructure and refine their phonological awareness from shallow, implicit sensitivity of large phonological units (i.e., syllables) down to a deep, explicit awareness of small phonological units, which develops and strengthens the phoneme awareness as the most reliable predictor of reading achievement (for a review, see Melby-Lervåg et al., 2012) and difficulties in DYS children (in French: Piquard-Kipfer & Sprenger-Charolles, 2013; Lefèvre et al., 2023). Although GPCs make the children able to understand that words are made up of – and can be broken into – letters that represent sounds to learn words (Ziegler et al., 2008, 2014), not all phonological representations are accessible prior to reading acquisition (Ziegler & Goswami, 2005). The direction for converging orthographic and phonological units is still a matter of debate, at least in French, which raises the question of the phonological units that typically developing children and DYS children use for segmenting and accessing words in silent reading.

Syllables as phonological reading units

Following developmental dual-foundation models that accommodate dual-route models (Seymour, 2005), children's use of phonological units follows a sequence that progresses from small units (phonemes) to large units (e.g., rimes, syllables). Learning the grapheme-to-phoneme correspondences allow children to successfully acquire and apply sequential grapho-phonemic processing that, however, imposes an overload of the attentional and working memory resources. As reading experience increases, the robustness and automation of GPCs guide children to gradually abandon the laborious grapho-phonemic processing to switch to automated grapho-syllabic processing, which lightens the cognitive resources to map large phonological units with large orthographic units, to, finally, whole word recognition (Bastien-Toniazzo et al., 1999; Colé et al., 1999; Maïonchi-Pino et al., 2010a, 2010b). As proposed by Ehri (2005), syllables progressively unitize and consolidate a large set of isolated phonemes into a small set of syllable structures which allows grapho-syllabic processing to require "*fewer connections to secure the word in memory*" (Ehri, 2005, p. 175).

However, an alternative view points out that understanding that a letter – or a grapheme – corresponds to a phoneme to be perceived and isolated from a sound sequence is rather difficult (Anthony & Francis, 2005; Ziegler & Goswami, 2005). The *syllabic bridge hypothesis* (Doignon-Camus & Zagar, 2014; Vazeux et al., 2020), which is grounded in the Developmental Interactive Activation Model with Syllables (DIAMS; Doignon-Camus & Zagar, 2009), postulates that the first step of learning the spelling-to-sound correspondences relies on the mapping of available phonological units structured through repetitive oral exposures with available orthographic units. Since children have abilities to quickly learn and extract regularities in letter co-occurrences that correspond to orthographic syllables (for a review, see Arciuli, 2018), in particular, because syllable boundaries are clear-cut in French, this makes the mapping between orthographic syllables with phonological syllables that are available long before reading acquisition. An argument to support the grouping of individual letters into syllables comes from the *bigram trough hypothesis* (Seidenberg, 1987). In words, letter co-occurrences that straddle syllable boundaries are of lower frequency than letter co-occurrences that precede, or even follow, the syllable boundaries (e.g., the bigram 'rt' is of lower frequency than bigrams 'ar' or 'ti' in the word 'partir', *to leave*). This makes the syllable boundaries perceptually salient and the syllables functionally relevant (Doignon & Zagar, 2006; Doignon-Camus & Zagar, 2014). As such, this is coherent with the French language – an opaque syllable-timed language¹ – in which syllables are easier to detect and isolate than phonemes (Duncan et al., 2006, 2013) and allow children to bypass the non-systematic, irregular, and ambiguous correspondences between phonological (i.e., phonemes) and orthographic units (i.e., graphemes; e.g., the letter cluster 'poi' is easier to map to the syllable /pwa/ rather than to single phonemes /p/+/o/+/i/ which misleads with the correct representation). In turn, after learning the letters-to-syllables correspondences, children would become able to allocate their attentional and working memory resources to individual letters and understand that 'poi' are distinct letters that are connected to individual phonemes. Both the syllabic bridge hypothesis and DIAMS model fit with the non-implemented dual-route Interactive Activation model with Syllables that consider

¹ French is considered to be opaque since it is irregular in the phoneme-to-grapheme direction (e.g., one phoneme [e.g., /o/] may be represented either in a fine- [e.g., 'o'] or in coarse-grained graphemes [e.g., 'eau', 'aux', etc.]; Fayol & Jaffré, 2008).

syllables as functional reading units to segment and access words in adults (IAS, Mathey et al., 2006). Such a model includes two paths to retrieve lexical representations. First, a direct orthographic path connects the letter level to the lexical level and an indirect phonological path links the letter level to an intermediate syllable level that spreads activation to the lexical level. Two complementary processes account for how activation spreads from the letter level to the syllable level and then to the lexical level. When a letter cluster is displayed, the letter level activates the syllable level via facilitatory prelexical between-level connections (between syllables and words; e.g., ‘par’ pre-activates the syllable /paʁ/ in /paʁtiʁ/, *to leave*, /paʁɔl/, *speech*, /paʁdɔ̃/, *sorry*, etc.), which, in turn, fires inhibitory lexical within-level connections due to the cohort of lexical competitors between words that share the same initial syllable. If the facilitatory prelexical between-level activation exceeds the inhibitory lexical within-level activation, this results in facilitatory syllable effects but on the contrary, this leads to inhibitory syllable effects. To date, a bunch of research in French typically developing children corroborated the idea that the spelling-to-sound correspondences are rather unclear at the phoneme level, so the grapho-phonemic processing could not be the first step to decode and recode words but rather the grapho-syllabic processing through the *syllable compatibility effect* (a better detection of a CV or CVC syllable [for consonant-vowel and consonant-vowel-consonant syllables] if it matches the first-syllable word structure [e.g., ‘BA’ in ‘balance’, *scale*, in which the syllable segmentation is ‘ba.lance’ or ‘BAL’ in ‘balcon’, *balcony*, in which the segmentation is ‘bal.con’; the dot stands for the syllable boundaries] rather than if it mismatches [e.g., ‘BAL’ in ‘balance’ or ‘BA’ in ‘balcon’]; Maïonchi-Pino et al., under review a; Chetail, & Mathey, 2009a, 2009b, 2012, 2013; Doignon & Zagar, 2006; Doignon-Camus & Zagar, 2014; Vazeux et al., 2020). In tasks that involve a lexical access, Chetail and Mathey (2009a, 2012, 2013) showed that beginning and poor readers ($M = 90.0$ months, $SD = 3.0$; $M = 133.0$ months, $SD = 5.0$) exhibit a facilitatory syllable compatibility effect, stronger with CV than CVC syllables, but an inhibitory syllable compatibility effect with both CV and CVC syllables in good readers. Beginning and poor readers would have imprecise and scarce phonological syllable representations, which could delay the connection between letter level and the syllable level and lower the activation strength. Thus, the between-level activation could be weak to pre-activate syllables and could slow down the activation sent to the lexical level to trigger a within-level inhibition that underlies lexical competition. This results in a facilitatory syllable compatibility effect. On the contrary, advanced and good readers ($M = 102.0$ months, $SD = 0.8$; $M = 131.0$ months, $SD = 0.5$; $M = 141.0$ months, $SD = 5.0$) would have precise and robust phonological syllable representations. This allows a quick and automatic pre-activation of syllables that strongly sent activation to the lexical level, which triggers a lexical competition that returns an inhibitory syllable compatibility effect. As a corollary, high-frequency orthographic and phonological syllables entail an inhibitory syllable compatibility effect since activation strength increases and quickly and strongly propagates to the lexical level to trigger a lexical competition, while low-frequency orthographic and phonological syllables trigger a facilitatory syllable compatibility effect since the connections between the letter level and the syllable level are low and slow, so activation that spreads to the lexical level decreases and prevents lexical competition (for a review, see Chetail & Mathey, 2010). However, whether, how, and when the syllables become fundamental reading units in developmental dyslexia remain unaddressed.

Phonological syllables in developmental dyslexia

According to the degraded/under-specified (or over-specified) phonological representation hypothesis, DYS children should struggle to use and access phonological syllables to segment and/or access words. Indeed, DYS children are supposed to have poor and imprecise phonological representations, which prevent the connection between orthographic and phonological units. However, this is not as straightforward as it seems. Previous studies with French native speaking DYS children regarding the status of phonological syllables are rare and mention some inconsistencies in their abilities to use syllables (Colé & Sprenger-Charolles, 1999; Doignon-Camus et al., 2013; Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2010b). For instance, Maïonchi-Pino et al. (2010b) showed a facilitatory syllable compatibility effect with high-frequency phonological syllables in a task that did not involve lexical access (i.e., a printed syllable detection at the initial of a word) in DYS children ($M = 121.3$ months, $SD = 12.2$) like their CA ($M = 123.7$ months, $SD = 12.2$) and RL peers ($M = 81.3$ months, $SD = 3.1$), which has been interpreted as efficient grapho-syllabic processing. With low-frequency phonological syllables, however, DYS children (like RL peers, not CA peers who exhibited a syllable compatibility effect)

exhibited a facilitatory *syllable length effect* (i.e., a CV syllable was detected faster than a CVC syllable whatever it matched or mismatched the first-syllable word structure (e.g., ‘BA’ in ‘balance’ or ‘balcon’ > ‘BAL’ in ‘balance’ or ‘balcon’), which has been described as grapho-phonemic processing. To account for their results, Maïonchi-Pino et al. (2010b) hypothesized that DYS children, through repetitive exposure to reading, have built a *mental syllabary* that stores pre-compiled ortho-phonological syllable representations for high-frequency syllables, whereas low-frequency syllables have been decoded and recoded online via the grapho-phonemic processing. Beyond these counterintuitive observations, Maïonchi-Pino et al. (2010b) concluded that DYS children were developmentally delayed with *potentially* underspecified phonological procedures partly compensated by longer exposure to reading, typically developing children demonstrating a generalized syllable compatibility effect with high- and low-frequency CV and CVC syllables. However, this interpretation raises some concerns. First, if grapho-syllabic processing ensues from grapho-phonemic processing, this is unfounded to claim that DYS children regress to the use of GPCs since these children are impaired in identifying and discriminating phonemes. This preference for CV syllables could basically stem from the prevalence of overrepresented simple CV syllables over underrepresented complex CVC syllables in first-syllable word structure in French polysyllabic words (60% of CV structures vs. 17% of CVC structures; Léon, 2011). This makes even more sense with low-frequency phonological syllables. Then, if DYS children built a mental syllabary with high-frequency syllables, this is conceivable that DYS children simply exhibited their abilities – though fragile regarding their slowness – to parse and extract orthographic regularities in favorable contexts with clear syllable boundaries (i.e., syllable compatibility) and without cognitive demands (i.e., no lexical access). Now, no discussion addressed the role of orthographic regularities that are essential to automatically connect sublexical orthographic units to sublexical phonological units. Considering the IAS model, an interpretation of Maïonchi-Pino et al.’s (2010b) results could be that the facilitatory syllable compatibility effect with high-frequency phonological syllables resulted from a prelexical between-level facilitation with high-frequency letter clusters that marked syllable boundaries to quickly activate the letter level that strongly spread activation to the syllable level since there was no, or at least no robust, activation sent to the lexical level to trigger a lexical within-level inhibition. The facilitatory syllable length effect with low-frequency phonological CV syllables ensued from an attenuated prelexical between-level facilitation possibly obstructed by low-frequency letter clusters that shadowed the syllable boundaries, amplified by the underrepresentation of low-frequency phonological CVC syllables.

This view accommodates the work by Doignon-Camus et al. (2013) who found that DYS children ($M = 129.0$ months, $SD = 10.0$) exhibited an inability to use phonological syllables alone to locate and segment pseudowords in a task that did not tap into lexical access, while having preserved abilities to learn and extract orthographic regularities. This resulted in the use of syllable-based segmentation strategies in contexts in which syllable boundaries were defined by both orthographic and phonological frequencies (i.e., the bigram trough). Taken together, these studies exemplified the controversies regarding the use phonological syllables with a focus on phonological and/or orthographic frequencies in tasks that did not inform us about the sublexical-lexical connection in DYS children, which is essential in natural reading contexts.

The present study

For the first time, we adapted a word-spotting paradigm in silent reading (Cutler, & Norris, 1988; in Spanish native-speaking typically developing children, see Álvarez et al., 2017) to disentangle whether the DYS children’s phonological deficit stems from impaired access to phonological representations and/or from degraded/under-specified phonological representations. Of interest is that this task requires sublexical processing and lexical access, which is a critical consideration because different tasks involve different word recognition processes. Children have to detect a visually displayed CVC syllable-sized word (e.g., ‘col’, *collar*) embedded at the beginning of a pseudoword whose syllable boundary was compatible (e.g., ‘colpu’ in which the segmentation should be ‘col.pu’; the dot stands for the syllable boundary) or incompatible (e.g., ‘colèd’ in which the segmentation should be ‘co.lèd’). Detecting the word within the pseudoword requires segmenting the pseudoword into smaller sublexical syllable units while identifying the word as a real French word requires accessing its lexical representation. Both processes are intended to reflect the efficiency and quality of these two levels of representation, and how they interact. If syllables are functional units for DYS children, in French, the word should be detected

faster in ‘colpu’ since the syllable boundary is between ‘l’ and ‘p’ while it is between ‘o’ and ‘l’ in ‘colèd’, which prevents from straightforwardly identifying the word ‘col’. As such, a word-spotting paradigm represents an *ideal* trade-off between tasks that are either perceptually (e.g., illusory conjunction paradigm) and/or cognitively *complex* (e.g., visual masked priming paradigm) and *simple* tasks (e.g., visual syllable detection task) that involve few levels of representation and processing, which may bias performance and favor close-to-normal phonologically-based response patterns in DYS children (e.g., Ramus, & Ahissar, 2012). As such, how to assess the quality of the orthographic and phonological representations should involve a minimum of resources and processing (Ramus & Ahissar, 2012; Ramus et al., 2013). Knowing that DYS children are characterized by impaired working memory (Berninger et al., 2008), which is useful for the retention and manipulation of letter and sound sequences, the word-spotting paradigm does not saturate working memory since the pseudowords remain on screen until the children responded although DYS children were required to explicitly and quickly access to phonological and lexical representations. Thus, we determined whether phonological syllables are functional units during visual word processing, an unresolved issue in French native speaking DYS children. Assuming the IAS and DIAMS models (Doignon-Camus & Zagar, 2009; Mathey et al., 2006), qualitative phonological representations (i.e., syllables) determine how effective the mapping between orthographic and phonological representations and, hence, the strength between prelexical between-level facilitation and lexical within-level inhibition and the direction of the syllable effects. In children with intact, precise phonological sublexical representations, the automatic and parallel activation of orthographic and phonological processes that underlie lexical access should be efficient and quick (e.g., Chetail, & Mathey, 2013). As a logical consequence, as exposure to print increases sensitivity to orthographic regularities is supposed to gradually improve orthographic representations whereas the parallel GPC learning is expected to improve the availability and quality of both sublexical orthographic and phonological representations and, hence, lexical representations. In our task that did require lexical access, the initial CVC phonological syllable should be pre-activated even stronger when the segmentation was compatible (e.g., ‘col’ pre-activates /kol/) and should trigger inhibitory syllable compatibility effects due to the lexical competition.

Hence, we raised a threefold research question that assumes the degraded access hypothesis and adjusts previous results in typically developing children who ran a task that implied a lexical decision as follows: if DYS children have intact orthographic and phonological syllable-sized representations (i.e., syllable-based detection and segmentation abilities), they should be identifying the CVC syllable-sized words in the compatible condition faster than in the incompatibility condition (i.e., we expected a facilitatory syllable compatibility effect; Hypothesis #1); however, if DYS children have built robust lexical representations through repetitive exposures to their orthographic representations, they should be exhibiting an inhibitory syllable compatibility effect for high-frequency CVC syllable-sized words due to lexical inhibition in the syllable compatibility condition (i.e., we expected a greater facilitatory syllable compatibility effect for CVC syllable-sized words with low-frequency phonological syllables; Hypothesis #2); if DYS children have degraded or impaired access to intact orthographic and phonological syllables, they should be slower – but not less accurate – than typically developing CA and RL peers, while still showing frequency-modulated syllable compatibility effects (Hypothesis #3).

Method

Participants

All of the children were tested between January and May 2019. We first recruited 25 DYS children (14 boys [56.0%] and 11 girls [44.0%]) who were referred by speech and language therapists based on a full-scale diagnosis of developmental dyslexia by neuropsychologists working in hospital-based pediatric services (i.e., mixed dyslexia with impaired lexical and sublexical reading skills) within the past 24 months. The DYS children exhibited no neurological, sensory, or psychological disorders. Additional criteria included the absence of comorbid attention deficit hyperactivity disorder (ADHD), the absence of inadequate intellectual, psychological, or educational backgrounds (i.e., a pIQ above 80 [$M = 99.8, SD = 6.6$], and a vIQ below 110 [$M = 100.3, SD = 7.8$]). All of the children were monolingual native speakers of French from an upper-medium socio-economic class and were recruited from six urban elementary schools (France). The DYS children had benefited from weekly reading- and phonological awareness-based interventions for less than 24 months. Twenty-five chronological age-matched typically developing peers (CA peers; 15 boys [60.0%] and 10 girls [40.0%]) and 25 reading

level-matched typically developing peers (RL peers, 13 boys [52.0%] and 12 girls [48.0%]) were matched with the DYS children². To determine an up-to-date reading level, all of the children completed an individual 20-min French standardized age-based word reading test. TIMÉ 3 (Écalle, 2006) was designed for children from 9-to-15 years old (but also applies to children from 7-to-9 years old). TIMÉ 3 assesses the level and accuracy of children’s orthographic and phonological knowledge, respectively. No analysis was carried out on their responses. We used them to (1) ensure that the CA and RL peers did not experience reading disorders and had adequate reading age-based profiles, (2) include CA and RL peers who performed as “normal-to-good readers,” (3) match the RL peers with DYS children who were confirmed to be delayed by at least 18 months in their reading development ($M_{\text{delay in months}} = -26.6$, $SD = 3.4$, $\text{range} = -33$ to -19). The CA and RL peers did not have reading levels that differed by more than 9 months from their chronological age ($M_{\text{difference in months}} = 2.1$, $SD = 4.2$, $\text{range} = -6$ to $+9$). Pairwise Student’s *t*-tests were run on chronological age and reading level to compare DYS children with CA and RL peers. Finally, all of the children were tested with a French translation of the Edinburgh Handedness Inventory - Short Form (Veale, 2014) to assess their handedness ($M_{\text{handedness}/100} = 76.0$, $SD = 49.5$, $\text{range} = -87.5$ to 100.0). All of the children participated after their parents had completed and signed an informed consent form. The Regional School Management Office and the Local Ethics Committee approved this research. The detailed profiles are provided in Table 1.

Table 1

Profiles and descriptive data for the children with developmental dyslexia (DYS children), the chronological age-matched children (CA), and the reading level-matched children (RL).

Group	<i>N</i> (boys/girls)	<i>CA</i>	<i>RL</i>	<i>Laterality</i>	<i>Diagnosis</i>	<i>Intervention</i>
DYS children	25 (14/11)	121.6 (3.0)	95.0 (4.5)	72.5 (56.4)	16.9 (3.4)	12.5 (3.8)
		116–126	87–107	–87.5–100	12–24	5–20
RL peers	25 (13/12)	94.0 (4.6)***	95.1 (4.3)	77.0 (48.4)	N/A	N/A
		87–104	88–105	–87.5–100		
CA peers	25 (15/10)	121.8 (2.7)	124.9 (5.3)***	78.5 (45.0)	N/A	N/A
		117–126	117–134	–75–100		

Notes. Asterisks (***) indicate a significant 0.0001 *p*-value; CA refers to chronological age; RL refers to reading level as measured by TIMÉ 3; ages are expressed in months, standard deviations are in brackets; ranges are below means and standard deviations; diagnosis indicates the elapsed time since the initial diagnosis of dyslexia; intervention indicates the duration of the reading- and phonological awareness-based interventions.

Material

Sixty-three-letter monosyllabic words were selected from the French lexical Manulex database, which provides grade-level word frequencies for elementary school-aged children (Lété et al., 2004). Lexical frequency was manipulated ($n = 31$ high-frequency words; $n = 29$ low-frequency words). All the words were C_1VC_2 syllables with regular spelling-to-sound correspondences (i.e., mute or multiple spelling-to-sound final C_2 were avoided; e.g., /s/, /t/). All the CVC words were possible initial C_1VC_2 syllables in polysyllabic words (e.g., ‘col’, *collar*, can be found in ‘colporter’, *to peddle*, etc.). Phonological frequency in the initial position was manipulated, while the number of homophones ($M = 3.07$, $SD = 2.33$) and the orthographic neighborhood ($M = 7.19$, $SD = 2.25$) were estimated, using Manulex-infra database (Peereman et al., 2007), which provides grade-level sublexical frequencies for French elementary school-aged children ($n = 28$ high-frequency syllables; $n = 32$ low-frequency syllables). Hence, a high-frequency word could be either a high-frequency C_1VC_2 syllable (e.g., ‘mur’, *wall*) or a low-frequency C_1VC_2 syllable (e.g., ‘lac’, *lake*), and a low-frequency word could be either a high-frequency C_1VC_2 syllable (e.g., ‘cor’, *horn*) or a low-frequency C_1VC_2 syllable (e.g., ‘mec’, *guy*). All the words were embedded in five-letter disyllabic pseudowords. Words were presented twice either in a syllable segmentation compatibility condition (e.g., ‘col’ in ‘colpu’ in which the segmentation

² Overall, we tested 103 typically developing children. Based on their scores at TIMÉ 3 and their personal information, we excluded 53 of them (51.5%) from the initial set because 28 (52.8%) were either the same chronological age or the same reading level as the previously selected CA or RL peers to match the DYS children, 19 (35.9%) were “poor readers” (i.e., typically developing children with $M_{\text{delay in months}}$ between -9 months and -17 months), 4 (7.4%) did not follow the instructions, and 2 dropped out (3.8%).

should be ‘col.pu’), or in a syllable segmentation incompatibility condition (e.g., ‘col’ in ‘colèd’ in which the segmentation should be ‘co.lèd’). In the syllable compatibility condition, all of the disyllabic pseudowords had an intervocalic C₂C₃ cluster (i.e., C₁V₁C₂C₃V₂; e.g., ‘lp’ in ‘colpu’). All of the intervocalic C₂C₃ clusters were considered unattested both in word-initial position and syllable-initial structures in French (e.g., Dell, 1995).

To focus on the phonological syllable as an essential sublexical unit, we also maximized the suppression of statistical and distributional orthographic information across the syllable boundaries (i.e., the bigram trough). Although it has been shown that orthographic properties do not occur isolated from phonological properties in French (Doignon & Zagar, 2006; Doignon-Camus & Zagar, 2014), they have been proposed to be a crucial non-phonological cue for syllable segmentation that DYS children are still sensitive to – and have developed knowledge about – explaining orthographic syllable segmentation strategies (Doignon-Camus et al., 2013; but see Fabre, & Bedoin, 2003; Maïonchi-Pino et al., 2012). To control for these properties, we combined the use of Manulex-infra (Peereman et al., 2007) and the Surface database computed from the Lexique 2 database (New et al., 2004), which provided us with the distributional and positional sublexical frequencies for the C₁V₁, V₁C₂, C₂C₃, and C₃V₂ bigrams. Consequently, we ensured that there was no clear bigram trough or, if so, that it did not fall within the expected syllable location (i.e., in ‘colpu’, the bigram trough was in ‘pu’, while in ‘colèd’, it was in ‘èd’). The list of C₁V₁C₂ monosyllabic words is provided in the Appendix. Orthographic and phonological distributional properties are summarized in Table 2.

Table 2

Orthographic and phonological distributional properties of the syllable-sized monosyllabic words.

		Frequency	<i>M</i> (<i>SD</i>)	Range
Lexical frequency	High-frequency words		347 (1006)	11–4811
	Low-frequency words		2 (3)	0–9
Phonological syllable frequency	High-frequency syllables		944 (1510)	113–6149
	Low-frequency syllables		22 (26)	0–94
Orthographic trigram frequency	High-frequency trigrams		1067 (1539)	208–7434
	Low-frequency trigrams		47 (56)	0–193
Incompatibility condition	2 nd bigram frequency (e.g., ‘ol’ in ‘colèd’)		2693 (1790)	341–16,370
	3 rd bigram frequency (e.g., ‘lè’ in ‘colèd’)		271 (188)	250–12,936
Compatibility condition	3 rd bigram frequency (e.g., ‘lp’ in ‘colpu’)		1572 (839)	0–3424
	4 th bigram frequency (e.g., ‘pu’ in ‘colpu’)		117 (102)	0–538

Notes. Frequencies are provided using the U₁-U₅ frequency which designates the mean frequency – occurrences per million – computed from the 1st to 5th grades; *M* refers to the mean; the standard deviations (*SD*) are in brackets.

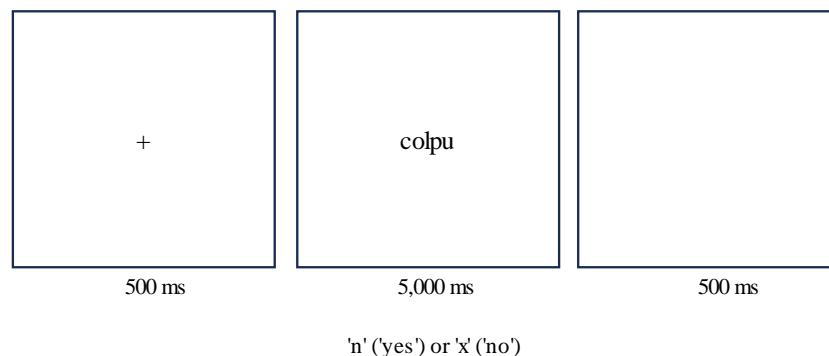
Procedure

All the children were tested individually in a single session ($M_{\text{duration}} = 9$ min, $SD = 1.$; range = 8–11) at home. Each child completed the French translation of the Edinburgh Handedness Inventory - Short Form (Veale, 2014), the French standardized age-based word-reading test (TIMÉ 3; Écalle, 2006), and the computer-driven word-spotting task. The script was designed, compiled, and run with E-Prime[®] 2 Professional (Psychology Software Tools, Inc., 2016) on Dell[®] Latitude 7490-series laptop computers with a 1920 × 1080 LCD screen resolution, a 60-Hz refresh rate, and running under Windows[®] 10. The software automatically recorded the response times (RTs henceforth) and response accuracy (RA henceforth). The lower-case letter pseudowords were black-colored, typed in Courier font on a white background. The children sat ± 60 cm from the screen. The initial CVC syllables covered a visual angle of 1.23° (all the pseudowords covered a visual angle of 2.05°). Each trial proceeded as follows: a centered black-colored fixation cross (+) was displayed for 500 ms, followed by a pseudoword that appeared at the center of the screen until the child responded (after 5000 ms, a warning message indicated the absence of response, which was considered to be an error). The next trial followed after a

500 ms delay (Fig. 1). The children were instructed to report as quickly and accurately as possible whether a real French word occurred at the beginning of a pseudoword. We did not pre-test whether the children were familiar or not with the stimuli. Before starting with a practice list ($n = 12$), we visually exemplified the task to help the children fully understand the instructions. No corrective feedback was provided during the practice list or the experimental lists. If the children identified a French word within the pseudoword (e.g., ‘col’ in ‘colpu’ or ‘colèd’), they had to answer ‘yes’ and press on an AZERTY keyboard on the green response key (i.e., ‘n’). If they did not identify a French word within the pseudoword, they had to answer ‘no’ and press on the red response key (i.e., ‘x’; the response should be ‘no’ to the pseudoword ‘tobti’ since neither ‘tob’ nor ‘tobt’ is a real French word). The children saw each word-bearing pseudoword twice, once in the syllable compatibility condition, and once in the syllable incompatibility condition, whereas they once saw the no-word-bearing pseudowords. All the stimuli were counterbalanced across six experimental lists (28 trials per list; 20 word-bearing pseudowords - ‘yes’ response - and 8 no-word-bearing pseudowords - ‘no’ response) that were separated by self-paced pauses. The distribution of the stimuli was pseudo-randomized (i.e., the same word, e.g., ‘col’ either in the syllable compatibility or in the syllable incompatibility condition was not presented in the same list, whereas the number of words presented in either the syllable compatibility condition or in the syllable incompatibility condition was equivalent). The order of presentation of the stimuli was randomized. To avoid decision bias in the experimental trials, we inserted two additional fillers that were different from the word-bearing and no-word-bearing pseudowords after each pause, which forced a ‘no’ response ($n = 12$; i.e., at the beginning of each experimental list), and the corresponding results were excluded from the statistical analysis.

Figure 1

Experimental design of the word-spotting paradigm.



Results

Overall, we collected 14,400 data points, of which 9000 were ‘yes’ responses (75 children \times 120 items). The analysis was conducted on ‘yes’ responses only. We used a restrictive three-step data standardization procedure for data inclusion. First, RTs associated with errors were excluded from the analysis ($n = 1116$; 12.4% of 9000 data), while responses provided after the 5000 ms time limit were considered errors ($n = 35$; 0.4% of 7,884 data). Then, correct RTs ≤ 400 ms (motor anticipation) and $\geq 4,000$ ms (late cognitive processes) were considered errors ($n = 202$; 2.6% of 7849 data). Finally, correct RTs were trimmed (for each child, RTs that deviated by ± 2.5 standard deviations from the mean for each CONDITION, syllable compatibility vs. syllable incompatibility, were normalized with each child’s mean substitution; $n = 186$; 2.4% of 7647 data).

Altogether, the error rate represented 15.0% of the 9000 ‘yes’ responses ($n = 1353$ errors). No child reached the random threshold ($50\% \pm 5\%$) after standardization (i.e., 61.7–98.3%), whereas items returned from 52.0 to 100.0% of correct responses. We did not use imputation methods to fill in the missing data (errors and converted-into-errors data were not real data). Due to model misspecification, i.e., non-normally skewed distribution, we used a log-normal transformation with the RTs (i.e., $\ln(x)$). We entered individual RA (correct = 1, error = 0) for each item as a dependent variable into Generalized Linear Mixed-Effects Models with a binomial distribution/logit link function (Lo & Andrews, 2015). Individual log-transformed RTs for each item as a dependent variable were entered into Linear Mixed-

Effects Models. CHILDREN and ITEMS were considered as random factors, while GROUP (DYS vs. CA vs. RL), CONDITION (compatibility vs. incompatibility), LEXICAL FREQUENCY (high vs. low), and PHONOLOGICAL SYLLABLE FREQUENCY (high vs. low) were entered as fixed factors. We submitted the $3_{\text{GROUP}} \times 2_{\text{CONDITION}} \times 2_{\text{LEXICAL FREQUENCY}} \times 2_{\text{PHONOLOGICAL SYLLABLE FREQUENCY}}$ mixed-design repeated-measures models to Jamovi 2.4.11 software (The Jamovi Project, 2023)³. When applicable, we used the p Bonferroni-Holm's adjusted α level for significance post hoc tests to control for the family-wise error rate for multiple comparisons.

All models successfully converged (bobyqa optimizer). Goodness-of-fit R^2_{LMM} and R^2_{GLMM} (Johnson, 2014) showed that fixed effects accounted for 9.2% of the variance ($R^2_{\text{marg}} = 0.0916$) for RA and 16.6% of the variance ($R^2_{\text{marg}} = 0.166$) for RTs, whereas all effects together (fixed and random) accounted for 29.6% of the variance ($R^2_{\text{cond}} = 0.296$) for RA and 48.8% of the variance ($R^2_{\text{cond}} = 0.488$) for RTs. To report M s, CIs, and Δ s, we back-transformed our lognormal data from \ln to ms with $e^{\ln(x)} = x$.

First, we inspected whether there was a relation between the individual scores obtained in TIMÉ 3 for each child within GROUP and their mean RTs and mean RA for each CONDITION, LEXICAL FREQUENCY and PHONOLOGICAL SYLLABLE FREQUENCY. We found systematic moderate-to-strong negative or positive correlations in DYS children only, while there is no – or weak – correlations whatever the dimension in CA peers ($-0.04 < r_{\text{RTs}} < 0.26$; $0.28 < r_{\text{RA}} < 0.49$) and RL peers ($-0.47 < r_{\text{RTs}} < -0.41$; $-0.17 < r_{\text{RA}} < 0.43$). The higher the scores in TIMÉ 3, the faster and the more accurate the DYS children whatever the CONDITION ($r_{\text{compatibility}} = -0.72$, $r_{\text{incompatibility}} = -0.63$ in RTs; $r_{\text{compatibility}} = 0.57$, $r_{\text{incompatibility}} = 0.74$ in RA), LEXICAL FREQUENCY ($r_{\text{low-frequency}} = -0.68$, $r_{\text{high-frequency}} = -0.66$ in RTs; $r_{\text{low-frequency}} = 0.64$, $r_{\text{high-frequency}} = 0.68$ in RA), and PHONOLOGICAL SYLLABLE FREQUENCY ($r_{\text{low-frequency}} = -0.58$, $r_{\text{high-frequency}} = -0.74$ in RTs; $r_{\text{low-frequency}} = 0.67$, $r_{\text{high-frequency}} = 0.66$ in RA).

Then, we inspected the decision-making process in DYS children and CA and RL peers by referring to the *signal detection theory* to assess the probability of a signal being detected in signal-alone vs. signal-plus-noise conditions (Hautus et al., 2021). We calculated the discrimination sensitivity threshold (i.e., the d' value indicates to what extent the children experienced difficulties in deciding whether a syllable was embedded in a pseudoword) and the decision criterion (i.e., the β value is the likelihood ratio that estimates the perception of the syllable). Both the d' value and β value were computed for each GROUP which show that the values are not normally distributed ($W_{d'} = 0.96$, $p = 0.03$; $W_{\beta} = 0.64$, $p < 0.0001$) with homogenous variances for the d' values, $F(2, 72) = 2.61$, $p = 0.08$ (not for the β values, $F(2, 72) = 5.60$, $p = 0.006$). A unidirectional ANOVA for GROUP is significant for the d' values, $F(2, 46.8) = 20.22$, $p < 0.0001$ and the β values, $F(2, 42.4) = 20.22$, $p = 0.006$. There are significant differences between DYS children and CA peers ($p_{d'} < 0.0001$; $p_{\beta} < 0.0001$) and RL peers ($p_{d'} = 0.04$; $p_{\beta} = 0.02$; no significant difference between CA and RL peers, $p_s > 0.1$). DYS children exhibit a low to low-moderate sensitivity to syllables with (very) difficult detection ($M_{d'} = 1.70$, $SD = 0.42$) and a quasi-unbiased decision toward the detection of syllables ($M_{\beta} = 0.99$, $SD = 0.49$), while CA peers ($M_{d'} = 2.34$, $SD = 0.28$) and RL peers ($M_{d'} = 2.21$, $SD = 0.31$) exhibit a low-moderate to moderate sensitivity to syllables with difficult to easier detection and a moderate conservative bias toward the detection of syllables (CA peers: $M_{\beta} = 1.83$, $SD = 1.53$; RL peers: $M_{\beta} = 1.33$, $SD = 0.36$).

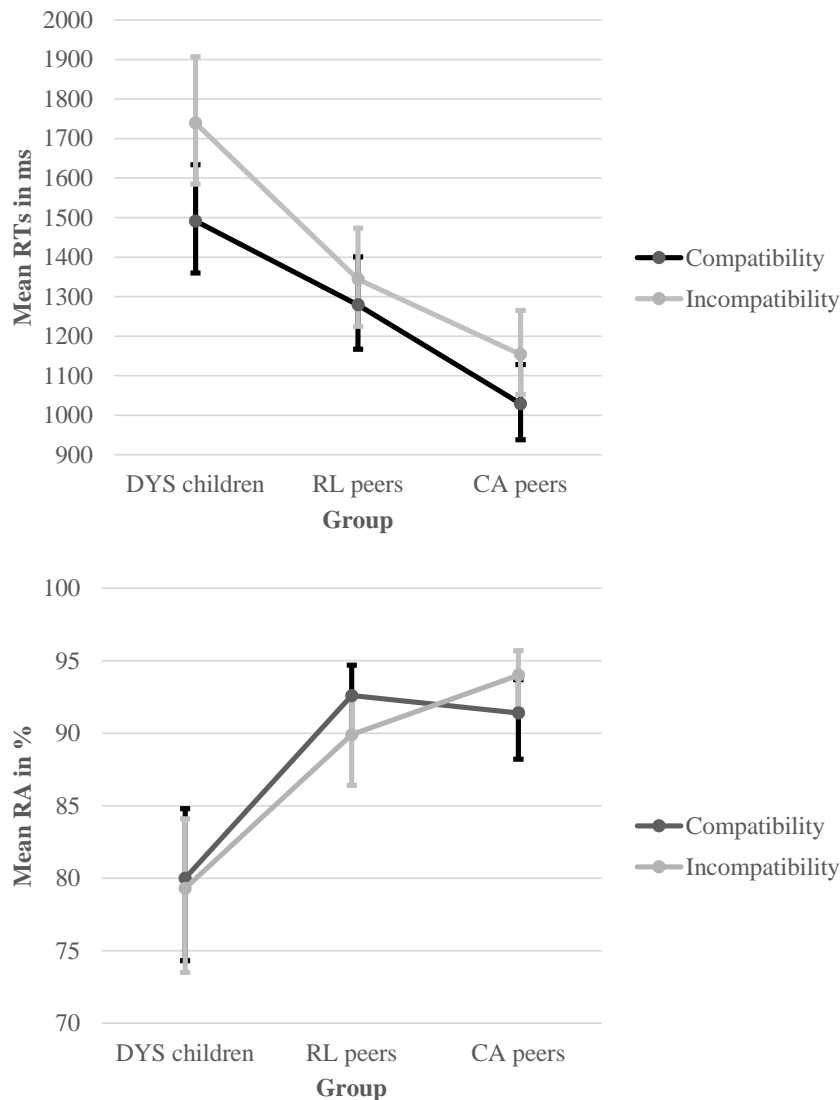
The GROUP main effect is significant in RTs, $F(2, 72.4) = 21.40$, $p < 0.0001$, 95% CI [998, 1758] and RA, $\chi^2 = 66.80$, $p < 0.0001$, 95% CI [75.0, 94.5]; $p_{\text{B-H}}$ post hoc tests show that DYS children were slower and less accurate ($M = 1610$ ms, 95% CI [1474, 1758]; $M = 79.7\%$, 95% CI [75.0, 83.6]) than CA peers ($\Delta = 520$ ms, $M = 1090$ ms, 95% CI [998, 1189], $t(72.5) = 6.54$, $p < 0.0001$; $\Delta = 13.1\%$, $M = 92.8\%$, 95% CI [90.7, 94.5], $z = -7.51$, $p < 0.0001$) and RL peers ($\Delta = 300$ ms, $M = 1310$ ms, 95% CI [1201, 1431], $t(72.5) = 3.44$, $p = .002$; $\Delta = 11.6\%$, $M = 91.3\%$, 95% CI [88.9, 93.3], $z = -6.33$, $p < .0001$). CA peers were faster ($\Delta = 220$ ms, $t(72.1) = 3.10$, $p = 0.003$) but not significantly more or less accurate than RL peers ($\Delta = 1.5\%$, $z = 1.23$, $p > 0.1$).

³ To discard uncovered factors that could affect our results, we inspected the ORTHOGRAPHIC TRIGRAM FREQUENCY since this is supposed to influence the activation strength between the letter level and the syllable level following predictions from the IAS model (Mathey et al., 2006). We did not carry out an additional analysis (e.g., by substituting the LEXICAL FREQUENCY) because values for LEXICAL FREQUENCY and ORTHOGRAPHIC TRIGRAM FREQUENCY strongly and positively correlate ($r = 0.86$).

The CONDITION \times GROUP interaction is also significant in RTs, $F(2, 7,448.2) = 15.57, p < 0.0001$, 95% CI [938, 1907] and RA, $\chi^2 = 16.31, p = 0.0003$, 95% CI [73.5, 95.7] (Fig. 2); p_{B-H} post hoc tests confirm that DYS children were faster in the compatibility condition ($M = 1491$ ms, 95% CI [1360, 1634]) than in the incompatibility condition ($\Delta = 248$ ms, $M = 1739$ ms, 95% CI [1585, 1907], $t(159.2) = 5.24, p < 0.0001$). CA peers were also faster in the compatibility condition ($M = 1029$ ms, 95% CI [938, 1128]) than in the incompatibility condition ($\Delta = 125$ ms, $M = 1154$ ms, 95% CI [1053, 1265], $t(151.0) = 4.01, p = 0.0008$), while the compatibility condition ($M = 1279$ ms, 95% CI [1167, 1401]) and the incompatibility condition ($\Delta = 65$ ms, $M = 1344$ ms, 95% CI [1225, 1473], $t(146.5) = 1.73, p > 0.1$) do not significantly differ in RL peers. Although there is no significant between-CONDITION difference in DYS children and CA and RL peers in RA ($p_s > 0.1$), there are significant between-GROUP differences between the compatibility condition and the incompatibility condition ($0.0001 < p_s < 0.02$).

Figure 2

Mean response times (RTs) in milliseconds (ms; upper panel) and mean response accuracy (RA) in percentage (%; lower panel) for the CONDITION \times GROUP interaction (DYS: children with developmental dyslexia; CA: chronological age-matched peers; RL: reading level-matched peers; bars represent 95% confidence intervals).

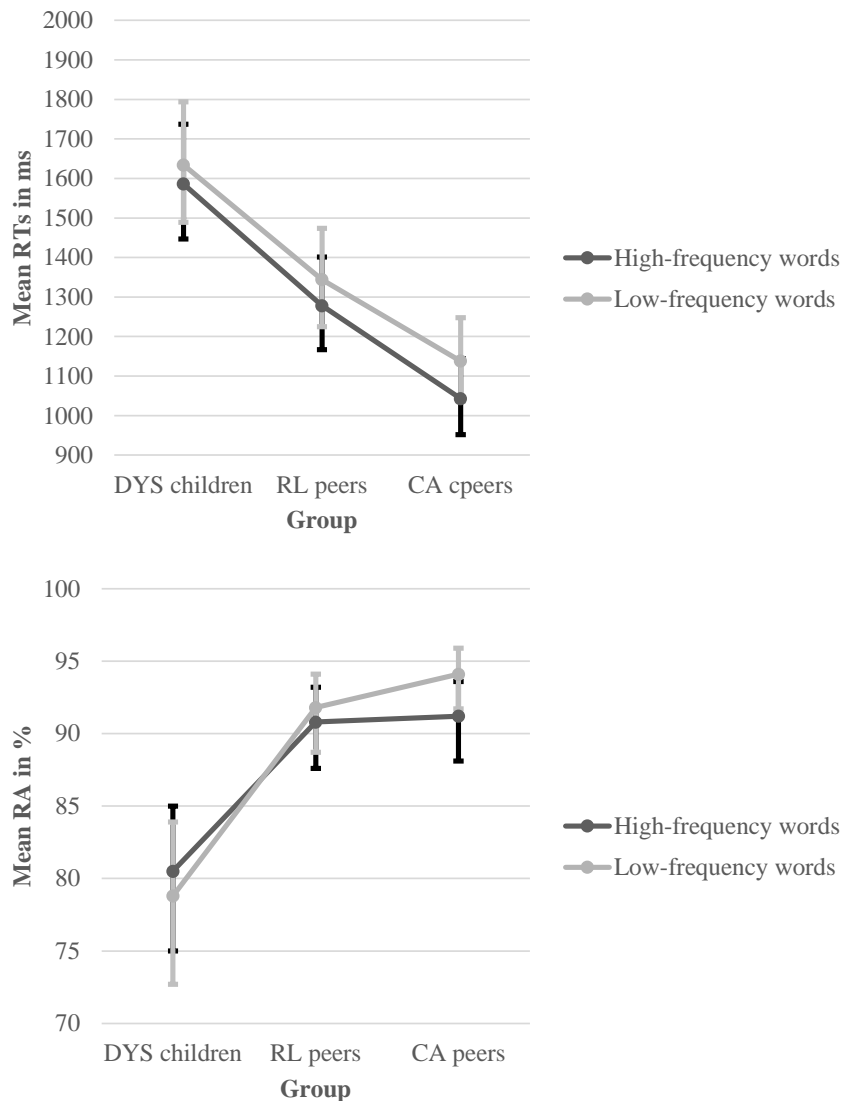


The LEXICAL FREQUENCY \times GROUP interaction is significant in RTs, $F(2, 7448.7) = 4.64, p = 0.01$, 95% CI [952, 1794] and RA, $\chi^2 = 10.61, p = 0.005$, 95% CI [72.7, 95.9] (Fig. 3); p_{B-H} post hoc tests reveal that CA peers detected high-frequency words faster ($M = 1043$ ms, 95% CI [952, 1144]) than low-frequency words ($\Delta = 95$ ms, $M = 1138$ ms, 95% CI [1037, 1248], $t(145.6) = 3.01, p = 0.02$), while

DYS children and RL peers do not significantly differ for high-frequency words ($M = 1586$ ms, 95% CI [1447, 1737]; $M = 1278$ ms, 95% CI [1167, 1401] respectively) and low-frequency words ($\Delta = 47$ ms, $M = 1634$ ms, 95% CI [1489, 1794], $t(159.2) = 1.02$, $p > 0.1$; $\Delta = 66$ ms, $M = 1344$ ms, 95% CI [1225, 1474], $t(146.5) = 1.74$, $p > 0.1$ respectively). Although there is no significant between-LEXICAL FREQUENCY difference in DYS children and in CA and RL peers in RA ($p_s > 0.1$), there are significant between-GROUP differences between high-frequency words and low-frequency words ($p_s < 0.0001$).

Figure 3

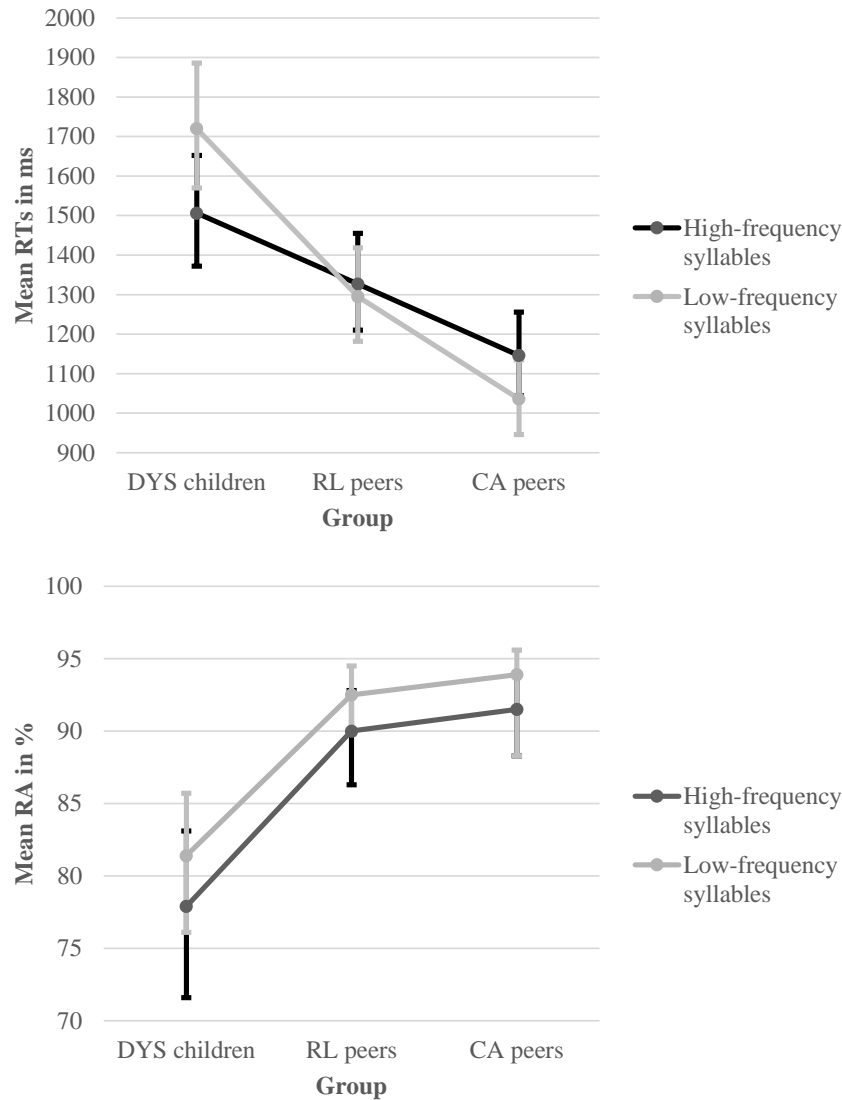
Mean response times (RTs) in milliseconds (ms; upper panel) and mean response accuracy (RA) in percentage (%; lower panel) for the LEXICAL FREQUENCY \times GROUP interaction (DYS: children with developmental dyslexia; CA: chronological age-matched peers; RL: reading level-matched peers; bars represent 95% confidence intervals).



The PHONOLOGICAL SYLLABLE FREQUENCY \times GROUP interaction is significant in RTs only, $F(2, 7447.9) = 77.07$, $p < 0.0001$, 95% CI [946, 1886] (in RA, $\chi^2 = 0.86$, $p > 0.1$, 95% CI [71.6, 95.6]; Fig. 4); p_{B-H} post hoc tests show that DYS children processed high-frequency syllables faster ($M = 1506$ ms, 95% CI [1372, 1652]) than low-frequency syllables ($\Delta = 214$ ms, $M = 1720$ ms, 95% CI [1570, 1886], $t(159.2) = 4.54$, $p < 0.0001$). CA peers processed low-frequency syllables faster ($M = 1036$ ms, 95% CI [946, 1135]) than high-frequency syllables ($\Delta = 110$ ms, $M = 1146$ ms, 95% CI [1044, 1256], $t(145.5) = 3.49$, $p = 0.004$), while high-frequency syllables ($M = 1327$ ms, 95% CI [1210, 1455]) and low-frequency syllables ($M = 1295$ ms, 95% CI [1182, 1418]) do not significantly differ in RL peers ($\Delta = 32$ ms, $t(146.5) = 0.85$, $p > 0.1$).

Figure 4

Mean response times (RTs) in milliseconds (ms; upper panel) and mean response accuracy (RA) in percentage (%) for the PHONOLOGICAL SYLLABLE FREQUENCY \times GROUP interaction (DYS: children with developmental dyslexia; CA: chronological age-matched peers; RL: reading level-matched peers; bars represent 95% confidence intervals).



The PHONOLOGICAL SYLLABLE FREQUENCY \times CONDITION \times GROUP interaction is significant in RTs, $F(2, 7447.9) = 4.50, p = 0.01, 95\% \text{ CI} [869, 2037]$ and RA, $\chi^2 = 9.38, p = 0.009, 95\% \text{ CI} [67.5, 96.8]$; p_{B-H} post hoc tests show that DYS children processed high-frequency syllables faster ($M = 1384 \text{ ms}, 95\% \text{ CI} [1249, 1533]$) than low-frequency syllables ($\Delta = 221 \text{ ms}, M = 1605 \text{ ms}, 95\% \text{ CI} [1454, 1772], t(156.9) = 3.58, p = 0.02$; not significant in RA, $z = 1.66, p > 0.1$) in the syllable compatibility condition only. CA peers processed low-frequency syllables faster ($M = 959 \text{ ms}, 95\% \text{ CI} [869, 1058]$) than high-frequency syllables ($\Delta = 144 \text{ ms}, M = 1103 \text{ ms}, 95\% \text{ CI} [997, 1222], t(146.8) = 3.47, p = 0.03$; not significant in RA, $z = 1.07, p > 0.1$) in the syllable compatibility condition only. There is no significant difference in RTs and RA in RL peers ($p_s > 0.1$).

The LEXICAL FREQUENCY \times PHONOLOGICAL SYLLABLE FREQUENCY \times CONDITION \times GROUP interaction is significant in RTs, $F(2, 7448.1) = 29.99, p < 0.0001, 95\% \text{ CI} [730, 2208]$ and RA, $\chi^2 = 26.12, p < 0.0001, 95\% \text{ CI} [56.2, 97.8]$. Since the CONDITION \times GROUP interaction is significant, we focus on the syllable compatibility condition to inspect the LEXICAL FREQUENCY \times PHONOLOGICAL SYLLABLE FREQUENCY interaction for each GROUP. The p_{B-H} post hoc tests reveal that DYS children detected high-frequency words with high-frequency syllables faster ($M = 1258 \text{ ms}, 95\% \text{ CI} [1129,$

1400]) than with low-frequency syllables ($\Delta = 354$ ms, $M = 1612$ ms, 95% CI [1431, 1813], $t(154.6) = 4.45$, $p = 0.003$), while there is no significant difference between high-frequency syllables ($M = 1524$ ms, 95% CI [1339, 1734]) and low-frequency syllables with low-frequency words ($\Delta = 75$ ms, $M = 1599$ ms, 95% CI [1438, 1778], $t(158.9) = 0.79$, $p > 0.1$). CA peers detected high-frequency words with low-frequency syllables faster ($M = 821$ ms, 95% CI [730, 925]) than with high-frequency syllables ($\Delta = 316$ ms, $M = 1137$ ms, 95% CI [1022, 1265], $t(148.5) = 5.89$, $p < 0.0001$), while there was no significant difference between high-frequency syllables ($M = 1072$ ms, 95% CI [943, 1217]) and low-frequency syllables with low-frequency words ($\Delta = 47$ ms, $M = 1119$ ms, 95% CI [1007, 1243], $t(145.4) = 0.72$, $p > 0.1$). There is no significant effect of LEXICAL FREQUENCY \times PHONOLOGICAL SYLLABLE FREQUENCY in RL peers ($p_s > 0.1$). At last, there are no significant between-LEXICAL FREQUENCY and/or between-PHONOLOGICAL SYLLABLE FREQUENCY differences in RA in DYS children and CA and RL peers ($p_s > 0.1$).

Discussion

In the long-debated issue about the multifaceted nature of the phonological deficit in DYS children, why they confuse and misuse the appropriate reading unit has been attributed to degraded/under-specified (or over-specified) phonological representations (Boada & Pennington, 2006; Snowling, 2001). However, what underlies this phonological deficit remains unclear. These children can *sometimes* exhibit phonological abilities, suggesting that phonological representations could be intact, but access to and retrieval from long-term memory could be impaired under cognitive and perceptual overload contexts (Ramus & Ahissar, 2012). Therefore, we aimed to determine whether, how, and when syllables, which are essential in French, are phonological units that are prelexically activated in DYS children. To do so, we used a word-spotting paradigm that simultaneously forced sublexical processing to segment a CVC syllable-sized word embedded in a pseudoword and required lexical processing to recognize the word.

Our main results indicate a mixture of both hypotheses. Crucially, we validate our Hypothesis #1 (CONDITION \times GROUP interaction). DYS children – CA peers too – use syllables to segment and even access words. The CVC syllable-sized words were identified faster when the syllables matched the syllable boundaries than when they mismatched (i.e., ‘col’ in ‘colpu’ – syllable compatibility condition – rather than ‘col’ in ‘colèd’ – syllable incompatibility condition) even in the absence or quasi-absence of orthographic statistical information across the syllable boundaries (i.e., the bigram trough). This, *a priori*, refocuses on the phonological – and not strict orthographic – nature of the syllable effects since the orthographic syllables did not match the phonological syllables (in Spanish; Alvarez et al., 2017; Luque et al., 2013; but see in French, Doignon-Camus et al., 2013). Of course, the preference for the syllable compatibility effect does not dismiss that DYS children have preserved their abilities to parse, extract, and use letter co-occurrences and statistical orthographic regularities to learn words that have often been encountered (i.e., statistical learning; Doignon-Camus et al., 2013; Saffran, 2018; but see Vandermosten et al., 2019).

As such, DYS children being able to parse and segment syllabically could be counterintuitive (Maïonchi-Pino et al., 2010b for similar observations). Given that they were diagnosed with poor phonological awareness, the degraded/under-specified (or over-specified) phonological representations hypothesis predicts that the precision of sublexical phonological representations should be affected (Colé & Sprenger-Charolles, 1999). Indeed, impaired phoneme representations should alter syllable representations. The DYS children were expected to differ in their abilities – and to be hindered by their inabilities – to identify phonological syllables that mediate lexical access during visual word recognition (Mathey et al., 2006). However, this does not seem so simple. First, DYS children are sensitive to CVC syllables, which are more complex, less frequent, and acquired later than CV syllables, and shape monosyllabic words (Doignon-Camus & Zagar, 2009; Lété et al., 2004; Maïonchi-Pino et al., 2010b) although the detection of the syllables is more difficult than in CA and RL peers (lower d' values). If DYS children have impaired, degraded phonological representations, no facilitatory syllable compatibility effect should have been found in particular when referring to previous studies in beginning and poor typically developing children who exhibited a weaker syllable compatibility effect with CVC syllables compared to CV syllables due to poor and imprecise representation of CVC syllables, which prevent lexical competition (Chetail & Mathey, 2009a, 2013).

A shortcut could be that imprecise or indistinct phoneme representations do not prevent syllables from being both segmental and prelexical reading units. Rather, we assume that DYS children have built phonological syllable representations through repetitive language exposures and use orthographic cues to free themselves from the laborious, tedious, and ambiguous grapheme-to-phoneme correspondences that readers face in French. This complies with the syllabic bridge hypothesis and DIAMS model in which “the first-ever connections between printed and spoken language are connections between letter groups and the available phonological syllables” (Doignon-Camus & Zagar, 2014, p. 1163). This could illustrate their abilities to use syllables and their difficulties with phonemes in reading assessment tests. In the end, this converges toward the proposal of Ehri (2005) who describes that grapho-syllabic processing requires “fewer connections to secure the word in memory” (p. 175), but it contradicts her claim that grapho-syllabic processing stems from the consolidation and unitization of grapho-phonemic processing first (Colé et al., 1999; Maïonchi-Pino et al., 2010a). If the answer does not lie in degraded phonological representations at the syllable level, the absence of an inhibitory syllable compatibility effect could ensue from a degraded propagation of the activation between the syllable level and the lexical level, and potentially degraded lexical representations, which prevents a quick and automatic activation of lexical competitors. This is a credible hypothesis since DYS children are slower and less accurate than both CA and RL peers.

Here, a critical piece of information is introduced since we half-validate our Hypothesis #2 (PHONOLOGICAL SYLLABLE FREQUENCY \times GROUP interaction, LEXICAL FREQUENCY \times GROUP interaction, and PHONOLOGICAL SYLLABLE FREQUENCY \times CONDITION \times GROUP interaction). Following the IAS model predictions (Mathey et al., 2006), the syllable compatibility condition pre-activates the initial CVC syllables, but high-frequency syllables should have triggered an inhibitory syllable frequency effect due to a quick and strong activation sent to the lexical level. We, indeed, found robust syllable frequency-modulated effects in DYS and CA peers. While CA peers show the expected inhibitory syllable frequency effect, DYS children exhibit a facilitatory syllable frequency effect. Until then, we concur with qualitative phonological syllable representations since we observe a facilitatory syllable compatibility effect. The concomitant presence of a facilitatory syllable compatibility effect and the absence of an inhibitory syllable frequency effect is therefore consistent with the idea that DYS children have, at least in part, precise sublexical phonological representations, which, however, do not activate lexical representations sufficiently. Both make the orthographic and phonological processes underlying the lexical access slow and apparently not less efficient (main effect of GROUP; Hypothesis #3). As such, this reflects an *under-optimally* activation spread from the syllable level – which contains qualitative phonological syllable representations – to the lexical level, compromising the accessibility, availability, and richness of lexical representations. Indeed, it is worth stressing that qualitative orthographic and phonological representations contribute to build and extend lexical representations (Harm & Seidenberg, 1999; see the *lexical quality hypothesis*; e.g., Perfetti & Hart, 2002; Perfetti, 2007). The absence of an inhibitory syllable frequency effect and the absence of the classical lexical frequency effect in DYS children, which, however, are found in CA peers yet (i.e., high-frequency words were detected faster than low-frequency words; LEXICAL FREQUENCY \times GROUP interaction), could dissociate from a *normal* syllable level activation that guides segmentation strategies but struggle with impoverished orthographic representations in their lexicon.

Finally, there was an additive *sublexical-lexical* effect in DYS children which we had not speculated on (LEXICAL FREQUENCY \times PHONOLOGICAL SYLLABLE FREQUENCY \times CONDITION \times GROUP interaction); a low-frequency syllable does not improve syllable segmentation with either high- or low-frequency words, whereas a high-frequency syllable drastically drives high-frequency word segmentation and access in the syllable compatibility condition. In CA peers, low-frequency syllables facilitate high-frequency word segmentation and access only, whereas there is no difference between high- and low-frequency syllables with low-frequency words. This observation confirms our aforementioned statement (i.e., “DYS children have, at least in part, precise sublexical phonological representations”). Precision relies on the sensitivity to and availability of high-frequency phonological syllables to segment and access words, in particular those that have been frequently encountered (i.e., consolidated and better represented), but fewer and slower than in CA children to trigger a lexical competition. Imprecision, though, stems from their insensitivity to low-frequency syllables although they benefit from comparable exposure to reading to that of CA peers. This informs us that DYS children have a more automatic access to high-frequency syllables than low-frequency syllables to segment and

access words. This qualifies the predominant view that attributes the phonological deficit to degraded phonological representations, which should affect the syllable representations whatever their structures (i.e., CV vs. CVC) or their frequency (i.e., high- vs. low-frequency).

A limitation to these results could lie in the procedure that we used. The children were tested one-by-one, at home. Regarding this context, we acknowledge that this did not represent a typical school or clinical context which potentially modulated the children's response patterns. Although there is no extensive available data for DYS children, it is well-known that socio-evaluative contexts influence stress/anxiety levels and affect performance in adults and students (for a review, see Kargiotidis & Manolitsis, 2023). Indeed, expecting a certain level of performance and/or monitoring the performance can induce distracting thoughts and worries leading to negative and intrusive self-instructions that overload and interfere with the working memory processing and phonological processing (i.e., *choking under pressure*; DeCaro et al., 2011). This point needs further investigation (e.g., Maïonchi-Pino et al., under review b).

In sum, in a *complex* paradigm that involves both sublexical and lexical processes (Ramus & Ahissar, 2012), phonological syllable representations are not as degraded as expected in DYS children as compared to CA and RL peers. Despite slowness and inaccuracy, they use phonological syllables and are influenced by their distributional properties to segment and access words. As can be seen from our results, there is a need to perform systematic comparisons of DYS children with both CA and RL peers on response times and response accuracy (Lefèvre et al., 2023). An in-depth inspection of the DYS children who were tested reveals a mixed deficit for most of them ($n = 17/25$ [68.0%] are both slower and less accurate than both CA and RL peers) who also have the lowest reading scores ($M = 19.7$, $SD = 1.2$ vs. $8/25$ [32.0%], $M = 22.4$, $SD = 1.7$). This subtends delayed and deviant reading profiles for these DYS children, while some DYS children ($5/8$ [62.5%]) are both faster and more accurate than their RL peers ($M_{DYS} = 1330$ ms, $SD = 202.8$, $M_{DYS} = 92.7\%$, $SD = 1.2$ vs. $M_{RL} = 1657$ ms, $SD = 113.7$, $M_{RL} = 88.0\%$, $SD = 1.3$; they behave like their CA peers, $M = 1219$ ms, $SD = 48.2$, $M = 93.5\%$, $SD = 1.7$). Our results draw attention to an asymmetrical double deficit that encompasses massive impaired access to sublexical and lexical representations (slowness) with selectively degraded phonological (weak sensitivity to low-frequency syllables) and lexical representations (inaccuracy) that should be considered for French. Although French is prone to highlight syllable-based effects, decentering from English-based studies questions the nature of the phonological deficit in DYS children and provides evidence for a deficit that does not affect the whole phonological sphere (Share, 2008). An alternative consideration for reduced neurophysiological connectivity between orthographic and phonological representations should not be discarded for regular and less regular orthographies (Wimmer & Schurz, 2010). Further investigation on sensitivity to universal phonological restrictions could also fuel the debate about why and how syllable identification and segmentation are effective in DYS children, particularly regarding previous studies on the importance of sonority, a phonological property of phonemes, which could cue and drive the segmentation strategies of clusters within and across syllable boundaries in printed words (Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2012, 2020).

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Appendix

Compatibility				Incompatibility			
High-frequency words		Low-frequency words		High-frequency words		Low-frequency words	
High-frequency syllables	Low-frequency syllables	High-frequency syllables	Low-frequency syllables	High-frequency syllables	Low-frequency syllables	High-frequency syllables	Low-frequency syllables
murna	gelvo	barfi	zipmo	muro	gelob	bariv	zipob
tirma	purfa	sirgo	kirpo	tiruv	purol	sirèv	kiroj
belgo	picta	forgu	tictu	beliv	picuj	forug	ticob
ferlu	bectu	docmè	tifga	ferob	becup	docap	tifub
balgu	bactè	calfi	nulpo	baléb	bacuf	calèg	nulig
filca	capto	vilma	cilca	filav	capuk	vilab	cilab
mervo	bolma	terpu	gagtu	meroj	bolém	terov	gaguj
carfi	vifga	corlu	pubjo	carib	viféj	coruj	puboj
verco	toctè	derlo	pifmè	veroj	tocug	derog	pifag
telvo	toptu		rabju	teluj	topév		rabuf
durni	secto		raptu	duril	secuf		rapik
sacti	lacti		valbi	sacub	lacub		valèd
surpi			rocmè	suril			rocav
volmu			bicta	volèb			bicav
selti			bipmo	selor			bipuv
solga			mecto	soléj			mecob
maldo			bobja	malèv			bobav
colpu			nefga	colèd			nefuk
parbo			ducme	parug			ducoj
			sucmè				sucog

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Author contribution

Norbert Maionchi-Pino and Damien Chabanal conceived, designed, and supervised this study. Norbert Maionchi-Pino and Master’ s students collected the data. Norbert Maionchi-Pino and Damien Chabanal analyzed and interpreted the data and wrote the paper. Norbert Maionchi-Pino and Elise Runge edited the text, figures, tables, and references. Norbert Maionchi-Pino, Elise Runge, and Damien Chabanal revised the paper. Norbert Maionchi-Pino, Elise Runge, and Damien Chabanal approved the submission of the manuscript for publication.

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Data availability

Data will be freely available on <https://osf.io/2m5xf/>.

Declarations

Ethics approval

The Regional School Management Office and the Local Ethics Committee approved this research (IRB00011540–2018–17).

Consent to participate

All children participated after their parents had completed and signed an informed consent form.

Conflict of interest

The authors declare no competing interests.