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ORIGINAL ARTICLE

A gradient-based preference for sonority markedness constraints in reading: evidence for intact phonological grammar in developmental dyslexia

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Abstract

How do children with developmental dyslexia process unattested or ill-formed phonological sequences in their native language? This question warrants attention because these children are primarily characterized by a phonological deficit. In this study, we support the hypothesis that intact phonological grammar allows segmenting and recognizing (pseudo)words through sensitivity to sonority markedness constraints. We administered a lexical decision task in silent reading to 21 French children with developmental dyslexia, comparing them with 21 chronological age-matched and 21 reading level-matched peers. Children were presented with words and pseudowords that either respected or transgressed syllable boundaries ((ar*gent), *money* vs. ⟨a*rgent⟩ vs. ⟨arg*ent⟩). For pseudowords, we manipulated the sonority profiles of unattested intervocalic ⟨C₁C₂⟩ clusters from unmarked, well-formed ((rj) in ⟨yrjyde⟩; high-fall) to marked, ill-formed clusters ((vl) in ⟨uvlyde⟩; high-rise). Results confirmed preferences for syllable segmentation in words ((ar*gent) is preferred to ⟨a*rgent⟩ or ⟨arg*ent⟩) regardless of distributional properties. We found a sonority projection effect that illustrated a gradient-based preference for sonority markedness constraints with pseudowords. However, pseudowords conforming to expected sonority-based segmentation ((yr*jyde) or ⟨u*vlyde⟩) were more difficult to reject, possibly due to interferences from lexical attestedness. We discuss a phonological deficit that does not stem from degraded language-specific or universal phonological representations.

Keywords: Neurodevelopmental language disorders; phonetics and phonology; reading

Abbreviations:

C, consonant

CA peers, chronological age-matched peers

DYS children, children with developmental dyslexia

RL peers, reading level-matched peers

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S, sonority

SP, sonority profile

V, vowel

Introduction

Research on speech perception has revealed that the listener's perceptual system attunes early and dynamically to sounds and sound sequences relevant to their native language (for a review, see Frost et al., 2019; Saffran & Kirkham, 2018). However, what will happen when children learning to read and those with reading disorders encounter phonological sequences that are unattested or ill-formed in their native language? To answer this question, we focused on the phonological segmentation strategies of DYS children compared to CA and RL peers in a lexical decision task. Through this investigation, we addressed the issue of the nature of the phonological deficit in DYS children. We aimed to demonstrate that the phonological deficit stems from degraded access to intact phonological syllable representations, while a gradient-based preference that follows sonority markedness constraints rooted in an active *universal grammar* guides the syllable segmentation of unattested, ill-formed intervocalic $\langle C_1C_2 \rangle$ clusters.

Sonority and sonority-based approach

Previous studies support the existence of a *sonority projection effect* to account for a fine-tuned, gradient-based preference for unattested well-formed onset clusters (e.g., /bn/) over unattested ill-formed clusters (e.g., /lb/; Albright, 2009; Daland et al., 2011; Hayes & White, 2013; for a review, see Berent, 2013). Evidence in speech perception and production, mostly in adults, shows a synchronically and gradually active repair of ill-formed onset clusters into well-formed ones with vowel epenthesis borrowed from the native stock of sounds (e.g., /lb/ \rightarrow /l**ə**b/ > /bd/ \rightarrow /b**ə**d/ > /bn/ \rightarrow /b**ə** n/; “>” stands for “preferred over”; in Brazilian Portuguese: Dupoux et al., 2011; in English: Davidson, 2006, 2011; Davidson & Shaw, 2012; Berent et al., 2007, 2011; in French: Maïonchi-Pino, Taki et al., 2015; in Japanese: Dupoux et al., 1999; Guevara-Rukoz et al., 2017; in Korean, Russian, or Hebrew: Berent et al., 2007, 2008, 2022; in Mandarin Chinese: Zhao & Berent, 2016; in Spanish: Berent, Lennertz, & Rosselli, 2012). For instance, Berent et al. (2007, 2008) and Berent, Lennertz, and Balaban (2012) claim that such a repair relies on active phonological recoding based on universal phonological constraints (i.e., by inserting an epenthetic vowel; e.g., /l**ə**bif/ > /lbif/). The authors rejected this repair as a consequence of a gestural failure to articulate ill-formed clusters (i.e., it seems to be impossible to pronounce /lb/ in onset clusters), a passive failure of acoustic-phonetic encoding, or an influence of phonetically grounded grammaticalization of unnatural sound sequences (Berent & Lennertz, 2010; but see Hayes & Steriade, 2004; Kirchner, 2004; Redford, 2008; Sun & Peperkamp, 2016; Wright, 2004). The sonority projection effect derives from the *sonority sequencing principle*, a universal phonological bias that cross-linguistically generalizes that the most well-formed onset requires a maximum sonority rise throughout the onset to the vowel

sonority value	1	2	3	4	5	6	7	8	9	10
low	—————→ high									
exemplars	/p/, /t/, /k/	/f/, /s/, /ʃ/	/b/, /d/, /g/	/v/, /z/, /ʒ/	/m/, /n/	/l/	/ʁ/	/i/, /y/, /u/	/o/, /e/, /ɔ/, /ɛ/	/a/
mode	voiceless	voiceless	voiced	voiced	nasals	laterals	rhotics	high	mid	low
	occlusives	fricatives	occlusives	fricatives				vowels	vowels	vowels

Figure 1. Sonority scale for French sounds based on the physical property of acoustic intensity (from 1 to 10). *Note.* This sonority hierarchy is adapted from Jespersen (1904, pp. 186–192; also see Gouskova, 2004) following Parker’s (2008) suggestion for ranking sounds according to their respective intensity (sonority values are partly arbitrary; however, the sonority distance between each mode has a value of 1). Some sounds are grouped under the same sonority value, although this classification is still debated (e.g., rhotics or /n/ and /m/; for a review, see Krämer & Zec, 2020). We did not represent glides because they were not relevant for our purpose.

(e.g., /bʁa/, $s_{[bʁ]} = +4$; $s_{[ʁa]} = +3$) and a minimal fall from the vowel throughout the coda (e.g., /aʁm/, $s_{[aʁ]} = -3$, $s_{[ʁm]} = -2$; Clements, 1990, 2009).

Although controversial in nature, *sonority* is described as a scalar phonological feature with quantifiable physical and perceptual properties. It categorizes all speech sounds into a hierarchical phonetically grounded scale, whose acoustic intensity is the most reliable correlate (Parker, 2008, 2012, 2017; Figure 1).

One perspective considers the sonority sequencing principle as a set of sonority markedness constraints grounded in universal grammar. These are abstract, hierarchically ranked phonological constraints that do not differ from one language to another, with differences arising from how each language orders and either minimally violates or maximally respects these constraints in *Optimality Theory* (Prince & Smolensky, 2004, 1997). The formalization of the phonological sonority markedness constraints is that an onset becomes more marked (illegal) and more ill-formed as the onset cluster sonority decreases from high-rise to high-fall sonority toward the vowel (e.g., /bna/ [unmarked – legal – well-formed] > /bda/ > /ba/ [marked – illegal – ill-formed]). Of interest is that this pattern reverses the phonotactic restrictions on the co-occurrence of sounds across syllable boundaries. The *syllable contact law* (Murray & Vennemann, 1983; Vennemann, 1988) attributes the well-formedness of syllable boundaries to a steep sonority fall between the coda and the onset (e.g., ⟨partir⟩, /pɑʁtʁ/, $s_{[ʁt]} = -6$, to leave). Gouskova (2004) extended and merged the sonority sequencing principle and the syllable contact law into a more sophisticated formalization of sonority markedness constraints through a stratified relational hierarchy implemented within Optimality Theory (for a review, see Pons-Moll, 2011). She considered sonority not in isolation but in relation to the adjacent individual sonorities of onset and coda, respectively. This generates SPs that are insensitive to the sonority value of individual onset and coda but sensitive to the *sonority distance* (i.e., rise, plateau, fall, etc.); hence, /ʁd/ and /mt/ belong to the same stratum (i.e., the same SP) and are theoretically equivalent because these clusters share the same sonority distance.

However, a crucial issue that does not consensualize is whether, and if so when, the sonority projection effect stems from (1) phonological generalizations from

lexical attestedness based on statistical and featural properties in the lexicon (e.g., unattested onset cluster /bn/ shares features with attested onset clusters /bɹ/ and /sn/; Albright, 2009; Bailey & Hahn, 2005; Daland et al., 2011; Hayes & Wilson, 2008), (2) dissociates from – but interacts with – attestedness and reflects a phonological bias (in French: Basirat et al., 2021; in English: Deschamps et al., 2015; Ettliger et al., 2012; Hayes & White, 2013; Vincent et al., 2022; White & Chiu, 2017; in German: Ulbrich et al., 2016; in Polish: Wiese et al., 2017), or (3) is innate, that is, as a part of universal grammar since unattested onset clusters have no statistical co-occurrences in the lexicon (Berent & Lennertz, 2010; Berent et al., 2007, 2008, 2011; Gómez et al., 2014). To determine whether the sonority projection effect lies in sonority markedness constraints, as a part of universal grammar, we investigated the segmentation strategies across syllable boundaries in silent reading in French-speaking DYS children. This point is an overlooked issue in DYS children who exhibit phonological deficits that remain unclear (Share, 2021).

Syllables as essential phonological reading units in French

Investigating sonority markedness constraints on syllable restrictions is appropriate in French. French is a syllable-timed language with clear-cut syllable boundaries, which allows non-canonical or complex onset clusters (e.g., ⟨VC⟩, ⟨CVC⟩, ⟨CCV⟩, etc.; Dell, 1995; Kaye & Lowenstamm, 1984; Léon, 2011) and polysyllabic words (> 90%; Lété et al., 2004).

Within Dual-Route models (Coltheart et al., 2001), children must first learn grapheme-to-phoneme correspondences via a phonological route to read new, regular, and unfamiliar words or pseudowords, which progressively builds a lexical route to read irregular and familiar words. Teaching the grapheme-to-phoneme correspondences allows children to understand that words consist of letters (the graphemes) that represent sounds (the phonemes) to learn words that they have heard but have never seen before (Ziegler et al., 2008, 2014, 2020).

This echoes Dual-Foundations models (Ehri, 2005; Seymour, 2005) which assume a phonological sequence that progresses from phonemes to syllables (phonological route) to whole-word recognition (lexical route). This view posits that syllables progressively unitize and consolidate a large set of isolated phonemes into a small set of syllable structures, allowing syllable processing to require “fewer connections to secure the word in memory” (Ehri, 2005, p. 175; also see Guo et al., 2023).

However, understanding that a letter – or a grapheme – corresponds to a phoneme being isolated from a sound sequence is rather difficult because phonemes are abstract phonological units (for a review, see Castles et al., 2018). Extensive literature on reading aloud and silent reading in French typically developing children supports the early role of syllables in segmenting and accessing words (from the end of Grade 1 to Grade 6; Bastien-Toniazzo et al., 1999; Chetail & Mathey, 2009a, 2009b, 2012, 2013; Colé et al., 1999; Maïonchi-Pino et al., 2010a; Sprenger-Charolles & Siegel, 1997; Vazeux et al., 2020).

A classical demonstration ensues from the expression of a *syllable compatibility effect* to account for syllables as segmental units: a word is segmented or identified faster when a syllable (⟨CV⟩ or ⟨CVC⟩) matches the syllable segmentation

(e.g., ⟨PA⟩ in ⟨pa.role⟩, *speech* or ⟨PAR⟩ in ⟨par.tir⟩, *to leave*; the dot represents the syllable boundaries) than when it mismatches the syllable segmentation (e.g., ⟨PA⟩ in ⟨par.tir⟩, ⟨PAR⟩ in ⟨pa.role⟩). Further evidence reveals that the structural properties (i.e., ⟨CV⟩ > ⟨CVC⟩ > ⟨CCV⟩) and statistical distribution (i.e., high- vs. low-frequency) of orthographically defined syllables by the *bigram trough* (Seidenberg, 1987; see further) and phonologically defined syllables derived from speech perception and production modulates the direction – that is, facilitation vs. inhibition – and the amplitude of both segmental and prelexical processes. An interpretation was proposed within the non-implemented dual-route Interactive Activation model with Syllables (IAS; Mathey et al., 2006). This model includes two routes to retrieve lexical representations. First, a direct orthographic route connects the letter level to the lexical level, and an indirect phonological route 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 (e.g., ⟨par⟩ pre-activates the syllable /paʁ/ and deactivates the syllables /baʁ/, /maʁ/, etc.), which, in turn, fires lexical within-level inhibition due to the cohort of lexical competitors between words that share the same initial syllable (i.e., /paʁtiʁ/, *to leave*, /paʁdɔ̃/, *sorry*, etc.). If the prelexical between-level activation exceeds the lexical within-level activation, syllable effect facilitation occurs, but this leads to syllable effect inhibition if the lexical within-level activation outclasses the between-level activation. Qualitative and quantitative phonological representations determine the effectiveness of the mapping between orthographic and phonological representations and hence the connection and activation strength between prelexical between-level facilitation and lexical within-level inhibition (Chetail & Mathey, 2009a, 2013).

Considering that phonemes are abstract phonological units, while syllables are phonological units available long before reading instruction (Duncan et al., 2006; Ziegler & Goswami, 2005), it has been proposed that syllables come into play early and are used first by children to decode and recode words. For instance, the *syllabic bridge hypothesis* (Doignon-Camus & Zagar, 2014; Vazeux et al., 2020) postulates that learning spelling-to-sound correspondences relies on the mapping of available phonological units with available orthographic units. Children can quickly learn and extract regularities from letter co-occurrences corresponding to orthographic syllables, which are gradually and straightforwardly connected to available phonological units. This would be even faster since the spelling-to-sound correspondences are less ambiguous at the syllable level than at the phoneme level (e.g., the word-letter cluster ⟨faim⟩, *hunger*, is easier to map to the syllable /fɛ/ rather than to single phonemes /f/+a/+i/+m/ which lead to the incorrect representation). In turn, after learning the letter-to-syllable correspondences, children can allocate their attentional resources to individual letters and understand that ⟨faim⟩ comprises distinct letters connected to individual phonemes.

Another robust argument arises from the clear-cut syllable boundaries in French. How letters co-occur within words does not follow a random distribution, even if the distribution varies across orthographies. The frequency and patterns of letter occurrences and co-occurrences within words are governed by language-specific

regularities that allow or ban certain positional associations (e.g., the bigram ⟨rt⟩ never occurs in French onset clusters but occurs in intervocalic positions; Dell, 1995). Based on abilities to parse and learn regularities in letter co-occurrences through statistical learning (Arciuli, 2018; Saffran, 2018), children could extract regularities across syllable boundaries to cluster letters into syllables early (Guo et al., 2023). Indeed, letter clusters that straddle the syllable boundaries are of lower frequency than letter clusters that precede or follow the syllable boundaries, which accounts for the grouping of letters into syllables and marking the syllable boundaries, referred to as the bigram trough (e.g., ⟨rt⟩ in ⟨partir⟩, *to leave*, is lower in frequency than ⟨ar⟩ or ⟨ti⟩ which defines syllables and syllable boundaries, Seidenberg, 1987). The bigram trough could act as a powerful statistical cue that makes the syllable boundaries perceptually salient and the syllables functionally relevant in visual word processing in French children (Doignon & Zagar, 2006; Doignon-Camus et al., 2013; Doignon-Camus & Zagar, 2014; Guo et al., 2023).

Although useful (for a review, see Chetail, 2015), the bigram trough is not a *sine qua non* condition since typically developing children and DYS children have been shown to locate syllable boundaries even in the absence or quasi-absence of distributional cues by relying on the individual sonority of consonants and SPs within intervocalic clusters (Berent et al., 2011; Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2012a, 2012b, 2012c, 2020; Maïonchi-Pino, de Cara et al., 2015; Marouby-Terriou & Denhière, 2002; see next paragraph). There are still few studies in silent reading in typically developing children – and even fewer in DYS children – that have focused on sonority, despite crucial literature demonstrating the importance of sonority in cluster reduction in children’s early speech production (i.e., ⟨CCV⟩ à ⟨CV⟩ or ⟨CVC⟩ à ⟨CV⟩; high-sonority consonants tend to be eliminated more frequently than low-sonority consonants, which preserves a maximal sonority distance; Demuth & McCullough, 2009; Ohala, 1999; Sprenger-Charolles & Siegel, 1997; for a discussion about sonority in children with phonological disorders, Klopfenstein & Ball, 2010; Wyllie-Smith et al., 2006).

Phonological grammar in developmental dyslexia

Developmental dyslexia is a genetic neurodevelopmental disorder that affects 3–15% of school-aged children and refers to an impaired acquisition of reading skills despite normal intellectual, psychological, social, or educational factors (Grigorenko et al., 2020; Snowling et al., 2020). To date, there has been no clear conclusion about the nature of the phonological deficit in developmental dyslexia (Ramus et al., 2013; Share, 2021), which tends to be a *universal* marker of reading difficulties (Landerl et al., 2013; Melby-Lervåg et al., 2012; Saksida et al., 2016; Ziegler, & Goswami, 2005).

While there is a consensus regarding the phonological deficit, its nature and origin can be accounted for by two contrasting views: the *degraded/under-specified (or over-specified) phonological representation hypothesis* and the *phonological access hypothesis*. The degraded/under-specified (or over-specified) phonological representation hypothesis asserts that the phonological deficit results from a categorical perception deficit. Such a deficit implicitly impacts the robustness and

distinctiveness of the phonological units essential for merging orthographic representations with phonological representations. This deficit manifests as difficulties at the acoustic-phonetic level in identifying and/or discriminating sounds that differ in a brief and single acoustic-phonetic transition (i.e., voicing; e.g., /ba/ vs. /pa/; for a review, see Noordenbos & Serniclaes, 2015).

The alternative hypothesis, the phonological access hypothesis, has received little attention. It supports the notion that the phonological deficit ensues from difficulties in memorizing, accessing, and retrieving intact phonological representations in contexts that impose perceptual and cognitive demands (e.g., lexical decision, speed or noise, etc.; Ramus & Ahissar, 2012). Evidence from studies in DYS children showed intact phonological abilities, both in the use of orthographic and phonological syllables and statistical regularities (Doignon-Camus et al., 2013; Maïonchi-Pino et al., 2010b, 2024), across different tasks, including those expected to highlight a phonological deficit in DYS children or adults (i.e., phonological grammar; Berent, Vaknin-Nusbaum et al., 2012; Berent et al., 2013, 2016; Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2012a, 2013; Marshall et al., 2011; Soroli et al., 2010; Szenkovits et al., 2016; Szenkovits & Ramus, 2005). The results in speech perception converged toward the recent proposal that the phonetic system dissociates from the phonological one, but impairments in acoustic-phonetic processing do not prevent normal phonological processing because the “*phonological deficit all but vanishes*” when the phonological grammar is considered (Berent et al., 2022, p. 498). Indeed, if the phonological deficit encompasses both the acoustic-phonetic and phonological systems although both have different representations (Berent et al., 2022), developmental dyslexia should impair the phonological grammar and suppress the gradient-based preferences for well-formed clusters over ill-formed ones. However, DYS children and adults gradually misperceived ill-formed onset clusters as well-formed ones, in the same way as typically developing children and adults (/lb/ → /ləb/ > /bd/ → /bəd/ > /bn/ → /bən/; in English and Hebrew: Berent, Vaknin-Nusbaum et al., 2012; Berent et al., 2013, 2016). They preferred well-formed syllable boundaries over ill-formed ones, thus segmenting within intervocalic clusters with well-formed clusters (e.g., /aʁ.zal/ > /a.ʁzal/). However, they preferred onset clusters with ill-formed syllable boundaries, thus segmenting before intervocalic clusters (e.g., /a.zʁal/ > /az.ʁal/; in French, Maïonchi-Pino et al., 2013).

These results were replicated in silent reading in French typically developing children and, to a modest extent, in DYS children. What has been shown reveals preferences to detect individual consonants in syllables that conform to the sonority sequencing principle (i.e., high-sonority coda > low-sonority coda and low-sonority onset > high-sonority onset), segment pseudowords whose syllable boundaries respect the syllable contact law (e.g., high-sonority coda + low-sonority onset ⟨lp⟩ > low-sonority coda + low-sonority onset ⟨db⟩ > low-sonority coda + high-sonority onset ⟨tl⟩), and prefer cluster reduction by removing sonorant consonants rather than obstruent ones (e.g., from ⟨tolpude⟩, ⟨topude⟩ > ⟨tolude⟩; Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2012a, 2012b, 2012c; Maïonchi-Pino, de Cara et al., 2015). A main concern related to these studies lies in the use of intervocalic ⟨C₁C₂⟩ clusters that have quantifiable orthographic and phonological statistical and distributional properties from which the children could have inferred their well-

formedness from attested structures in real French words (e.g., ⟨lp⟩ or ⟨rl⟩ in ⟨tolpude⟩ or ⟨torlade⟩; Basirat et al., 2021). Maïonchi-Pino et al. (2020), however, bypassed this issue with typically developing children and used intervocalic ⟨C₁C₂⟩ clusters that are unattested in French onset clusters but are either well-formed SPs (e.g., ⟨rz⟩) or ill-formed SPs (e.g., ⟨zm⟩). Their results revealed gradient-based preferences for well-formed SPs (high-fall SPs > low-fall SPs > plateau SPs > low-rise SPs > high-rise SPs), which followed the sonority-based markedness constraints formalized by Gouskova (2004).

The present study

To the best of our knowledge, the phonological grammar through the gradient-based sonority markedness constraints has never been gauged in silent reading in DYS children. Uncertainties persist as to the nature of the phonological deficit, although it affects their reading abilities. The present study aimed to determine whether DYS children have preserved abilities to use phonological syllable segmentation strategies and intact phonological grammar to locate and segment intervocalic ⟨C₁C₂⟩ clusters with null or quasi-null distributional properties while respecting or transgressing the gradient-based sonority markedness constraints (Gouskova, 2004).

To do so, we used a lexical decision task in an adapted version of the paradigm used by Treiman and Chafetz (1987): the children had to decide whether a printed stimulus, whose segmentation was cued in three possible positions, was a real French word or not (e.g., ⟨a*rgent⟩, /aʁʒɑ̃/, ⟨ar*gent⟩, or ⟨arg*ent⟩, *money*). Here, the best – expected – syllable segmentation is ⟨ar*gent⟩. Alternatively, the children saw a pseudoword whose segmentation was also cued in three possible positions where we manipulated the SPs of unattested intervocalic ⟨C₁C₂⟩ clusters from unmarked, well-formed SPs to marked, ill-formed SPs (high-fall SPs > low-fall SPs > plateau SPs > low-rise SPs > high-rise SPs). Here, a gradient-based preference following sonority markedness constraints favors the segmentation of high-fall SPs over plateau and high-rise SPs (e.g., ⟨yr*jyde⟩, /iʁʒid/ > ⟨ik*pyte⟩, /ikpit/ > ⟨oj*myze⟩, /ɔʒmiz/).

If one sticks to the degraded/under-specified (or over-specified) phonological representation hypothesis, which predicts imprecise, non-consolidated sublexical phonological representations, DYS children should be unable to use phonological syllable representations to segment and access words. We concur with the phonological access hypothesis. DYS children have intact orthographic and phonological sublexical representations, but their use for segmenting and accessing words in the lexicon is under-optimal. In the task that we proposed, which involved lexical decision, segmentation strategies, and comparisons between attested vs. unattested clusters, thereby overwhelming their short-term memory capacity and attentional resources, DYS children should then have more difficulties in retrieving and processing (pseudo)words. As a consequence, DYS children should be slower than CA and RL peers (Hypothesis #1) but should recognize words whose segmentation matches the syllable boundary (e.g., ⟨ar*gent⟩) faster than words

whose segmentation mismatches the syllable boundary (e.g., ⟨ar*gent⟩ > ⟨a*rgent⟩ or ⟨arg*ent⟩; Hypothesis #2).

Next, we adhere to Berent's (2013) hypothesis; humans are equipped with innate formally grounded constraints on syllable structure restrictions, which are expressed through algebraic optimization rules that guide the (dis)preferences of syllable structures. A universal phonological grammar that is not functionally grounded in constraints derived from the acoustic-phonetic properties of sounds should, therefore, confer the ability to process unattested intervocalic ⟨C₁C₂⟩ clusters even in the absence of statistical and distributional cues, following a gradient-based preference for syllable boundaries from unmarked, well-formed SPs (e.g., ⟨rj⟩) to marked, ill-formed SPs (e.g., ⟨vl⟩).

Further, if there is a dissociation between the phonetic and phonological systems (Berent, 2017; Berent, Vaknin-Nusbaum et al., 2012; Berent et al., 2013, 2016), even in the presence of an acoustic-phonetic deficit described as the *true* source of the phonological deficit in developmental dyslexia, which confuses and obstructs phoneme identification and discrimination, DYS children should be sensitive to such gradient-based preference for sonority markedness constraints and compensate for their acoustic-phonetic deficit through the top-down process from their intact phonological grammar (Berent et al., 2022). Hence, it would be easier for children to decide that ⟨y*rjyde⟩ is not a word (⟨rj⟩ is an unattested ill-formed onset cluster) compared with ⟨y*vlyde⟩ (⟨vl⟩ is an unattested well-formed onset cluster; Hypothesis #3). However, it would be more difficult for children to decide that ⟨ur*jyde⟩ is not a word (⟨rj⟩ is a well-formed syllable boundary) compared with ⟨iv*lyde⟩ (⟨vl⟩ is an ill-formed syllable boundary; Hypothesis #4).

Method

Participants

We first recruited 27 DYS children who were referred to by speech and language therapists and diagnosed with mixed profiles of developmental dyslexia (with impaired lexical and sublexical reading skills). We excluded six DYS children from the initial set because three (11.1%) were left-handed, two (7.4%) did not follow the instructions, and one (3.7%) was bilingual. Twenty-one DYS children who were diagnosed within the past 24 months and who had benefited from weekly reading- and phonological awareness-based interventions for less than 24 months were included. They had normal or corrected-to-normal vision and hearing and had no neurological, intellectual, emotional, or psychological disorders (based on parents' and teachers' self-reports or speech and language therapists' reports).

We then tested 66 monolingual typically developing children who regularly attended school in 2nd to 5th grade from three urban and peri-urban elementary schools in the Auvergne-Rhône-Alpes region (France). All the children were from the middle to the upper-middle socioeconomic class and had been taught to read for nine months at least, using a classical mixture of analytical grapheme-to-phoneme correspondences and global procedures (Sprenger-Charolles, 2019). No child repeated a grade or skipped. They were predominantly right-handed (measured using a French translation of the Edinburgh Handedness Inventory – Short Form;

Veale, 2014). They were submitted to an individual 20-min French standardized age-based word-reading test, TIMÉ 3 (Écalle, 2006), which allows group testing and can be used with children from 7 to 15 years old. TIMÉ 3 enables the inspection of the children's reading level by assessing the accuracy of the lexical representation level via the use of direct orthographic representations or indirect phonological representations. No analysis was carried out on their responses. We used it to (1) ensure that typically developing children did not experience any reading disorders and had adequate reading age-based profiles and (2) match the typically developing children with the DYS children based either on their chronological age (CA peers) or their reading level (RL peers). Regarding typically developing children, we used their scores in TIMÉ 3 and their personal information to exclude 24 of them (36.4%) because 17 (70.8%) were either of the same chronological age or of the same reading level as already selected CA and RL peers, five (20.8%) were left-handed, and two (20.8%) did not follow the instructions. We then matched the 21 DYS children to 21 CA and 21 RL peers.

All 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. Profiles and full descriptive data are provided in Table 1.

Material

We designed 35 six-letter long disyllabic $\langle V_1C_1C_2V_2C_3V_3 \rangle$ pseudowords (e.g., $\langle \text{otkyfe} \rangle$) based on the original material in Maïonchi-Pino et al. (2020). However, we made substantial changes to fix issues with some intervocalic $\langle C_1C_2 \rangle$ clusters ($n = 16/35$ [45.7%]). The three initial letters were still $\langle V_1C_1C_2 \rangle$ structures with no geminate, biphonemic grapheme (e.g., $\langle x \rangle$, $\langle ks \rangle$), digraph (e.g., $\langle ch \rangle$, $\langle f \rangle$), or mute consonant grapheme, but with a final $\langle V_3 \rangle$ schwa-like vowel (i.e., $\langle e \rangle$, $\langle \partial \rangle$), and $\langle C_2V_2C_3 \rangle$ structures in which V_2 was $\langle y \rangle$, the rarest vowel grapheme in French (i.e., $\langle i \rangle$; we used $\langle o \rangle$, $\langle o \rangle$ if $\langle y \rangle$ changes the pronunciation of $\langle C_2 \rangle$; e.g., with $\langle g \rangle$, $\langle g \rangle$, $\langle gy \rangle$ becomes $\langle \text{zi} \rangle$, so we used $\langle go \rangle$ which sounds $\langle go \rangle$; $n = 4/35$ [11.4%]).

All pseudowords had three consonants and three vowels that had regular spelling-to-sound correspondences. However, to ensure the reading and pronunciation of ambiguous $\langle V_1C_1 \rangle$ (e.g., $\langle ym \rangle$ and $\langle um \rangle$ which can be pronounced either $\langle im \rangle$, $\langle ym \rangle$, $\langle \epsilon \rangle$, or $\langle um \rangle$), we pretested five instances for each [$n = 10$] in different pseudowords (e.g., $\langle umgove \rangle$, $\langle umdzye \rangle$, $\langle ymdyle \rangle$, $\langle ymjuve \rangle$, etc.) with 24 typically developing children native speakers of French selected in Grade 2 [$n = 12$] and Grade 5 [$n = 12$]. We reported that $\langle ym \rangle$ was pronounced $\langle um \rangle$ [94.2%] while $\langle um \rangle$ was pronounced $\langle ym \rangle$ [96.7%]). All pseudowords had intervocalic $\langle C_1C_2 \rangle$ clusters which were ill-formed in both word-initial position and syllable-initial structures in French (Dell, 1995). However, some can be attested within real French words but were among the rarest ones (i.e., ≥ 0.25 [using cross-databases for positional token frequency, see below]; e.g., $\langle bn \rangle$; $n = 17/35$). No intervocalic $\langle C_1C_2 \rangle$ cluster had voicing differences (to avoid regressive/progressive assimilation), and we minimized homorganic consonants¹ (except for $\langle dl \rangle$ and $\langle lj \rangle$ to fulfill other distributional constraints). Although the intervocalic $\langle C_1C_2 \rangle$ clusters were ill-formed in initial

Table 1. Descriptive profiles (numbers, means, and standard deviations) of children with developmental dyslexia (DYS children), chronological age-matched peers (CA peers), and reading level-matched peers (RL peers)

Children's profiles	<i>n</i>	<i>M</i>	<i>SD</i>
Children with developmental dyslexia (DYS children)			
Gender (boy/girl)	12/9		
Laterality score		91.7	9.3
Diagnosis ¹		20.6	2.3
Reeducation ²		12.6	3.2
Chronological age		120.1	4.4
Reading level		92.5	2.9
Difference chronological age/reading level		-27.6	3.7
Chronological age-matched peers (CA peers)			
Gender (boy/girl)	13/8		
Laterality score		94.6	6.3
Chronological age		120.4	4.0
Reading level		123.3	5.1
Difference chronological age/reading level		2.9	4.7
Reading level-matched peers (RL peers)			
Gender (boy/girl)	12/9		
Laterality score		91.7	8.2
Chronological age		92.7	2.8
Reading level		93.0	2.9
Difference chronological age/reading level		0.3	2.9

Note: *N* = 63 (*n* = 21 per GROUP). Laterality scores are expressed in percentage (%) and reflect either left-handedness (from -100 to -50) or right-handedness (from 50 to 100). Diagnosis, reeducation, chronological ages, reading levels, differences between chronological ages and reading levels, associated means (*M*), and standard deviations (*SD*) are expressed in months. ¹ and ² were obtained thanks to the speech and language therapists.

positions, three segmentations – which were manipulated in the present study – were possible: $\langle V_1.C_1C_2V_2C_3V_3 \rangle$, $\langle V_1C_1.C_2V_2C_3V_3 \rangle$, or $\langle V_1C_1C_2.V_2C_3V_3 \rangle$. Whatever the segmentation, and regardless of whether the segmentation respected or violated the phonotactic restrictions of French, the syllable-initial structures were the rarest (i.e., $\langle V \rangle$ [8%], $\langle VC \rangle$ [1.9%], and $\langle VCC \rangle$ [0.5%]; Léon, 2011).

We extended the method of Maïonchi-Pino et al. (2020) by combining three up-to-date databases – compared to two in Maïonchi-Pino et al.'s (2020) study – to control and minimize the orthographic and distributional properties of the position-dependent sub-components of the $\langle V_1C_1C_2V_2C_3 \rangle$ pseudowords to null or quasi-null values (Lexique-infra 1.11, Gimenes et al., 2020; Manulex-infra, Peereman et al., 2007; Surface 2.10, New et al., 2004). We thus extracted the U_1 - U_5 token frequency computation (Grade 1 to Grade 5 instead of U_1 - U_2 – Grade

1 to Grade 2 – previously) from Manulex-infra, which provides grade-level sublexical frequencies for French elementary school readers, to take into account the age ranges of the children who were tested and extrapolate possible exposures to orthographic and phonological co-occurrences provided by sublexical databases in adults (Lexique-infra 1.11 and Surface 2.10). Importantly, there was no clear bigram trough whatever the intervocalic $\langle C_1C_2 \rangle$ clusters or SPs that we created. Distributional properties are reported in Table 2.

Ill-formed intervocalic $\langle C_1C_2 \rangle$ clusters were not duplicated and were subdivided into five SPs ($7 \langle C_1C_2 \rangle \times 5$) inspired by the gradient-based sonority markedness of Gouskova (2004), from the least marked (legal) and most well-formed syllable contact to the most marked (illegal) and most ill-formed syllable contact as follows: high-fall (e.g., $\langle lb \rangle$; $s = -4, -3, \text{ or } -2$), low-fall (e.g., $\langle fk \rangle$; $s = -1$), plateau (e.g., $\langle kp \rangle$; $s = 0$), low-rise (e.g., $\langle vn \rangle$; $s = +1$), and high-rise (e.g., $\langle zr \rangle$; $s = +2 \text{ or } +3$).

We also added 20 disyllabic, six-letter long real French words with initial $\langle V_1C_1C_2V_2 \rangle$ ($+\langle V_3C_3 \rangle$ or $\langle C_3V_3 \rangle$ or $\langle C_3C_3 \rangle$) structures and whose acknowledged segmentation is $\langle V_1C_1.C_2V_2 \rangle$ (e.g., $\langle \text{argent} \rangle$, *money*); orthographic and phonological syllable boundaries coincided. We subdivided them into high-frequency words ($n = 10$) and low-frequency words ($n = 10$) using the mean token frequency computed from Manulex (Lété et al., 2004) and Lexique 3.83 (New et al., 2004).

We also manipulated the orthographic and the phonological syllable frequencies using the mean token frequency in initial position computed from Manulex-infra (Peereeman et al., 2007), Lexique-infra (Gimenes et al., 2020), and Surface 2.10 (New et al., 2004), and we subdivided them into high-frequency ($n = 10$) and low-frequency orthographic syllables ($n = 10$) and into high-frequency ($n = 12$) and low-frequency phonological syllables ($n = 8$). Finally, we calculated the mean positional bigram frequency for the $\langle C_1C_2 \rangle$ clusters with the same methods and databases, and we found no systematic bigram trough ($n = 12/20$ [60.0%]). Distributional properties are reported in Table 3. A full list of the words and pseudowords is provided in the Appendix.

Procedure

The children were tested between March and July 2021. DYS children who were identified first participated first. They were tested individually in an undistracted and silent room in a single session. Neither the teachers nor the experimenters observed or supervised the children. No child missed the computer-driven task after completing the TIMÉ 3 and the Edinburgh Handedness Inventory – Short Form, interrupted the session, or quit the study.

The script was designed, compiled, and run with E-Prime® 3.0 Professional software (Psychology Software Tools, Inc., 2016) on Dell® Latitude laptop computers with a 1920×1080 LCD screen resolution, a 60-Hz refresh rate, and running under Windows® 10. The children were instructed to report whether the stimulus was a real French word or not. They had to press on the “green” (“yes”) or “red” (“no”) response keys (“n” and “x” keys on an AZERTY keyboard, respectively). The software automatically recorded the response times (RTs) and response accuracy (RA).

Table 2. Distributional positional properties for the sub-components of the pseudowords by orthographic and phonological frequencies, sonority profiles, and databases

Distributional properties	Database	Sonority profiles				
		High-fall	Low-fall	Plateau	Low-rise	High-rise
Orthographic frequencies						
Frequency for the V ₁ C ₁ bigrams (initial position)	Lexique-infra	6.1 (10.3)	4.3 (5.6)	11.5 (13.1)	7.2 (12.5)	0.0 (0.1)
	Manulex-infra	1.6 (2.7)	1.4 (2.7)	2.4 (2.8)	1.5 (2.3)	0.2 (0.4)
	Surface	19.6 (33.5)	4.4 (9.1)	6.2 (8.8)	10.9 (25.7)	0.3 (0.7)
	<i>M</i>	9.1 (20.8)	3.4 (6.2)	6.7 (9.6)	6.5 (16.2)	0.2 (0.5)
Frequency for the C ₁ C ₂ bigrams (that straddle the syllable boundary; all the C ₁ C ₂ bigrams have a null frequency in initial position; <i>M</i> = 0.0, <i>SD</i> = 0.0)	Lexique-infra	12.4 (19.5)	1.2 (3.0)	4.9 (10.5)	3.9 (8.6)	8.9 (22.5)
	Manulex-infra	13.9 (18.5)	1.0 (2.4)	1.4 (2.4)	10.0 (25.1)	3.9 (10.0)
	Surface	4.0 (8.7)	0.2 (0.4)	0.3 (0.6)	7.9 (20.9)	0.5 (1.3)
	<i>M</i>	10.1 (16.1)	0.8 (2.2)	2.2 (6.2)	7.3 (18.6)	4.4 (13.9)
Frequency for the C ₂ V ₂ bigrams (that follow the syllable boundary; within position; counted once per SP if used twice or thrice; e.g., (go))	Lexique-infra	67.3 (156.9)	79.2 (153.8)	94.9 (167.2)	8.4 (11.8)	34.9 (37.5)
	Manulex-infra	64.8 (152.8)	73.9 (149.7)	75.7 (168.2)	14.7 (33.4)	30.7 (37.8)
	Surface	65.9 (288.9)	66.0 (146.4)	76.7 (160.9)	5.3 (11.1)	20.6 (23.4)
	<i>M</i>	66.0 (142.9)	7.0 (141.0)	82.4 (153.5)	9.4 (20.5)	28.7 (31.0)
Frequency for the V ₁ C ₁ C ₂ trigrams (initial position)	Lexique-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Manulex-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.1)	0.0 (0.0)	0.0 (0.0)
	Surface	0.0 (0.0)	0.0 (0.0)	0.1 (0.3)	0.0 (0.0)	0.0 (0.0)
	<i>M</i>	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

(Continued)

Table 2. (Continued)

Distributional properties	Database	Sonority profiles				
		High-fall	Low-fall	Plateau	Low-rise	High-rise
Frequency for the $C_1C_2V_2$ trigrams (within position)	Lexique-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Manulex-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Surface	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	<i>M</i>	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Frequency distance between V_1C_1 bigrams and C_1C_2 bigrams (bigram trough; negative value = presence of a bigram trough)	Lexique-infra	6.4 (22.8)	-3.2 (5.7)	-6.6 (20.3)	-3.3 (16.9)	8.9 (22.5)
	Manulex-infra	12.4 (18.2)	-0.5 (3.7)	-1.0 (4.1)	-8.5 (25.8)	3.7 (10.1)
	Surface	-15.6 (29.1)	-4.2 (9.2)	-5.9 (8.9)	-3.0 (36.0)	0.2 (0.6)
	<i>M</i>	1.0 (25.7)	-2.6 (6.5)	-4.5 (12.6)	0.7 (26.6)	4.3 (14.0)
Frequency distance between C_1C_2 bigrams and C_2V_2 bigrams (bigram trough; negative value = presence of a bigram trough)	Lexique-infra	-42.9 (152.7)	-122.1 (182.8)	-63.3 (133.9)	-3.3 (15.5)	-30.2 (49.4)
	Manulex-infra	-41.6 (148.5)	-116.1 (178.7)	-52.7 (140.2)	-2.6 (42.4)	-20.1 (34.5)
	Surface	-52.5 (137.7)	-108.5 (175.0)	-55.6 (136.3)	3.4 (25.0)	-26.4 (20.6)
	<i>M</i>	-45.7 (139.0)	-115.6 (169.8)	-57.2 (129.9)	-0.8 (28.4)	-25.6 (35.1)
Phonological frequencies						
Frequency for the V_1C_1 syllables (initial position; counted once per SP if used twice or thrice; e.g., /yl/)	Lexique-infra	2,731.8 (6,675.6)	9.3 (17.5)	15.3 (24.5)	13.0 (23.9)	9.3 (24.3)
	Manulex-infra	3,327.6 (8,145.8)	6.5 (11.8)	25.3 (59.2)	21.6 (54.9)	0.4 (0.7)
	Surface	2,379.7 (5,790.8)	6.7 (9.5)	378.5 (894.2)	332.4 (825.5)	1.7 (2.4)
	<i>M</i>	2,813.0 (6,530.5)	7.5 (12.6)	139.7 (516.3)	122.3 (487.2)	3.8 (14.0)

(Continued)

Table 2. (Continued)

Distributional properties	Database	Sonority profiles				
		High-fall	Low-fall	Plateau	Low-rise	High-rise
Frequency for the V ₁ C ₁ C ₂ syllables (initial position)	Lexique-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Manulex-infra	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	Surface	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	<i>M</i>	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Frequency for the C ₂ V ₂ syllables (within position)	Lexique-infra	710.0 (461.5)	708.6 (796.2)	643.7 (530.3)	1,035.1 (617.4)	1,477.0 (504.2)
	Manulex-infra	602.1 (349.1)	629.0 (732.3)	634.4 (624.4)	982.0 (532.7)	1,331.3 (294.2)
	Surface	1,176.5 (829.0)	1,423.2 (2,217.7)	1,725.9 (2,234.9)	1,861.7 (1,102.3)	2,464.0 (663.3)
	<i>M</i>	829.5 (609.8)	920.2 (1,345.6)	1,001.3 (1,378.4)	1,292.9 (851.3)	1,757.4 (699.4)

Note: Frequencies are given by token occurrences; standard deviations are provided in brackets.

Table 3. Distributional positional properties for the sub-components of the words by orthographic and phonological frequencies, lexical frequency, and databases

Distributional properties	Database	Frequency					
		Low-frequency			High-frequency		
		<i>M</i>	<i>SD</i>	<i>Range</i>	<i>M</i>	<i>SD</i>	<i>Range</i>
Orthographic frequencies							
Frequency for the V ₁ C ₁ bigrams (initial position; counted once per frequency if used twice or thrice; e.g., ⟨ar⟩)	Lexique-infra	605.3	606.1	21.1–1,781.3	8,653.0	9,659.2	2,308.4–27,007.9
	Manulex-infra	534.4	641.2	5.5–1,582.4	4,898.3	4,586.1	1,339.4–13,453.1
	Surface	995.9	917.8	68.7–2,457.8	5,273.3	3,441.1	2,534.5–10,697.5
	<i>M</i>	711.9	727.7		6,274.9	6,637.3	
Frequency for the C ₁ C ₂ bigrams (that straddle the syllable boundary; within position; counted once per frequency if used twice or thrice; e.g., ⟨rg⟩)	Lexique-infra	452.0	320.1	76.9–1,026.0	4,866.2	3,277.8	1,536.9–11,088.3
	Manulex-infra	592.9	701.0	163.0–2,147.0	4,505.2	3,128.3	1,041.5–9,802.3
	Surface	221.2	286.0	49.5–842.6	980.8	657.4	341.3–2,398.4
	<i>M</i>	422.0	476.8		3,450.7	3,096.1	
Lexical frequency	Lexique	4.0	3.1	0.3–8.8	55.0	106.5	5.3–354.5
	Manulex	2.2	2.8	0–9	35.6	63.7	1–202
	<i>M</i>	3.4	2.4		48.6	91.5	
Phonological frequencies							
Frequency for the V ₁ C ₁ syllables (initial position; counted once per frequency if used twice or thrice; e.g., /al/)	Lexique-infra	165.7	210.9	12.1–615.0	1,907.5	1,967.8	577.7–4,835.3
	Manulex-infra	195.3	190.4	0.9–442.0	1,611.2	1,174.5	629.0–3,309.8
	Surface	405.9	452.5	18.6–733.5	3,010.3	3,059.4	1,366.2–7,595.4
	<i>M</i>	255.6	312.5		2,176.3	2,092.9	

Note: Frequencies are given by token occurrences; standard deviations are provided in brackets.

The stimuli were displayed in black-colored lowercase letters typed in Courier font on a white background. The words and pseudowords were displayed one at a time. They were segmented by an asterisk (i.e., “*”) placed either (1) before the $\langle C_1C_2 \rangle$ cluster (e.g., $\langle y^*rjyde \rangle$), (2) within the $\langle C_1C_2 \rangle$ cluster (e.g., $\langle yr^*jyde \rangle$), or (3) after the $\langle C_1C_2 \rangle$ cluster (e.g., $\langle yrj^*yde \rangle$). The children sat approximately 60 cm from the screen. The stimuli covered a visual angle of approximately 2.46°. Each trial proceeded as follows: a centered, black-colored fixation cross (+) was displayed for 500 ms, followed by a word or a pseudoword, which appeared at the center of the screen until the child responded (after 5,000 ms, a warning message indicated the absence of response, and this was labeled as an error). The next trial followed after a 750-ms delay. First, the children were trained with a practice list ($n = 10$). No corrective feedback was provided on the practice list and the experimental lists.

Our material resulted in two conditions (i.e., word, “yes” responses vs. pseudoword, “no” responses). In both conditions, each word and pseudoword was displayed three times by undergoing the three segmentations as follows: $\langle V_1^*C_1C_2V_2 \rangle$, $\langle V_1C_1^*C_2V_2 \rangle$, or $\langle V_1C_1C_2^*V_2 \rangle$ ($n_{\text{words}} = 60$; $n_{\text{pseudowords}} = 105$). The conditions and segmentations were counterbalanced across five experimental lists (i.e., 33 trials per list; 12 “yes” responses and 21 “no” responses) that were separated by self-paced pauses. The distribution of the stimuli was pseudo-randomized (i.e., the same word or pseudoword was not presented in the same list, whereas the number of segmentation types was equivalent; i.e., 11×3). The order in which the stimuli were presented was randomized. To avoid decision bias, we inserted two additional fillers after each pause ($n = 10$; i.e., at the beginning of each experimental list), and the corresponding results were excluded from the statistical analysis.

Results

We collected 11,655 data points, of which 3,780 were “yes” responses and 6,615 were “no” responses. We preprocessed and analyzed data for “yes” and “no” responses separately. We used a restrictive three-step data processing procedure for data inclusion. First, RTs associated with errors were excluded from the analysis ($n_{\text{yes}'} = 103$, [2.7%]; $n_{\text{no}'} = 122$ [1.8%]). No correct RT was ≤ 400 ms (motor anticipation) or $\geq 4,000$ ms (late cognitive processes). Then, correct RTs were trimmed (for each child, RTs that deviated by ± 2.5 standard deviations from the mean for each segmentation type were replaced by the respective mean of each segmentation type; $n_{\text{yes}'} = 90$, [2.5%]; $n_{\text{no}'} = 124$ [1.9%]). We did not use imputation methods to fill in missing data. No child reached random threshold ($50\% \pm 5\%$) after standardization (88.3% to 100.0%). No item returned null or random correct responses (71.4% to 100.0%).

Due to model misspecification (non-normally right-skewed distribution of the RTs; Skewness_{yes'}} = 1.89, Kurtosis_{yes'}} = 6.46; Skewness_{no'}} = 0.94, Kurtosis_{no'}} = 2.56), we used a log-normal transformation ($\ln(x)$; Skewness_{yes'}} = 0.96, Kurtosis_{yes'}} = 2.11; Skewness_{no'}} = 0.16, Kurtosis_{no'}} = 0.60). Log-transformed RTs for each item as a dependent variable were entered into Linear Mixed-Effects Models. CHILDREN and ITEMS were considered random factors, whereas GROUP (DYS children vs. CA peers vs.

RL peers), SEGMENTATION ($\langle V_1^*C_1C_2V_2 \rangle$ vs. $\langle V_1C_1^*C_2V_2 \rangle$ vs. $\langle V_1C_1C_2^*V_2 \rangle$), and either LEXICAL FREQUENCY, ORTHOGRAPHIC FREQUENCY, and PHONOLOGICAL FREQUENCY (high- vs. low-frequency; “yes” responses) or SONORITY PROFILE (high-fall vs. low-fall vs. plateau vs low-rise vs. high-rise; “no” responses) were fixed factors.

RTs that were standardized and converted into errors and the error rate represented 5.2% of the expected “yes” responses and 3.7% of the expected “no” responses. Due to ceiling effects, RA was not analyzed.

We submitted our mixed-design repeated-measures models to Jamovi 2.4.11 software (The Jamovi Project, 2023). All LMM models successfully converged (Bound Optimization By Quadratic Approximation [bobyqa] optimizer). Goodness-of-fit R^2_{margin} showed that fixed effects accounted for 23.6% (“yes”) and 41.1% (“no”) of variance, whereas all effects together (fixed + random effects; R^2_{cond}) accounted for 63.5% (“yes”) and 72.8% (“no”) of variance. When applicable, we used the *post hoc* p Bonferroni–Holm’s adjusted α level for significance to control the family-wise error rate for multiple comparisons (p_{B-H}). To report M s, CIs, and Δ s, we back-transformed the log-normal data from \ln to ms with $e^{\ln(x)} = x$.

For “yes” responses (i.e., words)², the main effect of GROUP was significant, $F(2, 60.6) = 15.51$, $p < .0001$, 95% CI (1,044, 1,365); DYS children recognized words more slowly ($M = 1,228$ ms, 95% CI [1,173, 1,286]) than CA peers ($\Delta = 135$ ms, $M = 1,093$ ms, 95% CI [1,044, 1,145], $t(60.7) = 3.61$, $p_{B-H} = .001$) but responded faster than RL peers, although the difference was not statistically significant ($\Delta = 76$ ms, $M = 1,304$ ms, 95% CI [1,244, 1,365], $t(60.6) = -1.87$, $p_{B-H} = .07$).

The SEGMENTATION main effect was also significant, $F(2, 36.1) = 20.57$, $p < .0001$, 95% CI (1,120, 1,291); the words were identified with the $\langle V_1C_1^*C_2V_2 \rangle$ segmentation faster ($M = 1,155$ ms, 95% CI [1,120, 1,192]) than the $\langle V_1^*C_1C_2V_2 \rangle$ segmentation ($\Delta = 95$ ms, $M = 1,250$ ms, 95% CI [1,212, 1,291], $t(36.1) = 6.38$, $p_{B-H} < .0001$) or the $\langle V_1C_1C_2^*V_2 \rangle$ segmentation ($\Delta = 56$ ms, $M = 1,211$ ms, 95% CI [1,174, 1,249], $t(36.0) = -3.79$, $p_{B-H} = .001$).

There was no significant main effect or interaction with either the LEXICAL FREQUENCY, ORTHOGRAPHIC FREQUENCY, or PHONOLOGICAL FREQUENCY factors ($p_s > .1$).

For “no” responses (i.e., pseudowords)³, the GROUP main effect was significant, $F(2, 60.0) = 35.25$, $p < .0001$, 95% CI (1,232, 1,631); DYS children rejected pseudowords more slowly ($M = 1,564$ ms, 95% CI [1,500, 1,631]) than CA peers ($\Delta = 280$ ms, $M = 1,284$ ms, 95% CI [1,232, 1,339], $t(60.0) = 6.73$, $p < .0001$) but did not significantly differ from RL peers ($\Delta = 46$ ms, $M = 1,610$ ms, 95% CI [1,544, 1,679], $t(60.0) = 0.99$, $p > .1$).

The GROUP \times SEGMENTATION \times SONORITY PROFILE interaction was significant, $F(16, 6,298.3) = 6.81$, $p < .0001$, 95% CI (1,103, 1,806) (Figure 2); we, therefore, inspected the SEGMENTATION \times SONORITY PROFILE interaction for each GROUP.

Whichever GROUP, there was a significant gradual decrease from high-fall SPs to high-rise SPs for $\langle V_1C_1^*C_2V_2 \rangle$ segmentation with systematic significant differences between both extreme SPs ($4.26 < t_s < 9.26$, $p_s < .02$). The difference between high-fall SPs and plateau SPs was significant in DYS children, $t(144.6) = 4.09$, $p = .04$ and CA peers only, $t(143.8) = 6.39$, $p < .0001$ (in RL peers, $t(143.3) = 2.91$, $p > .1$), while the difference between plateau SPs and high-rise SP was not significant whichever GROUP ($-3.77 < t_s < -1.34$, $p_s > .1$).

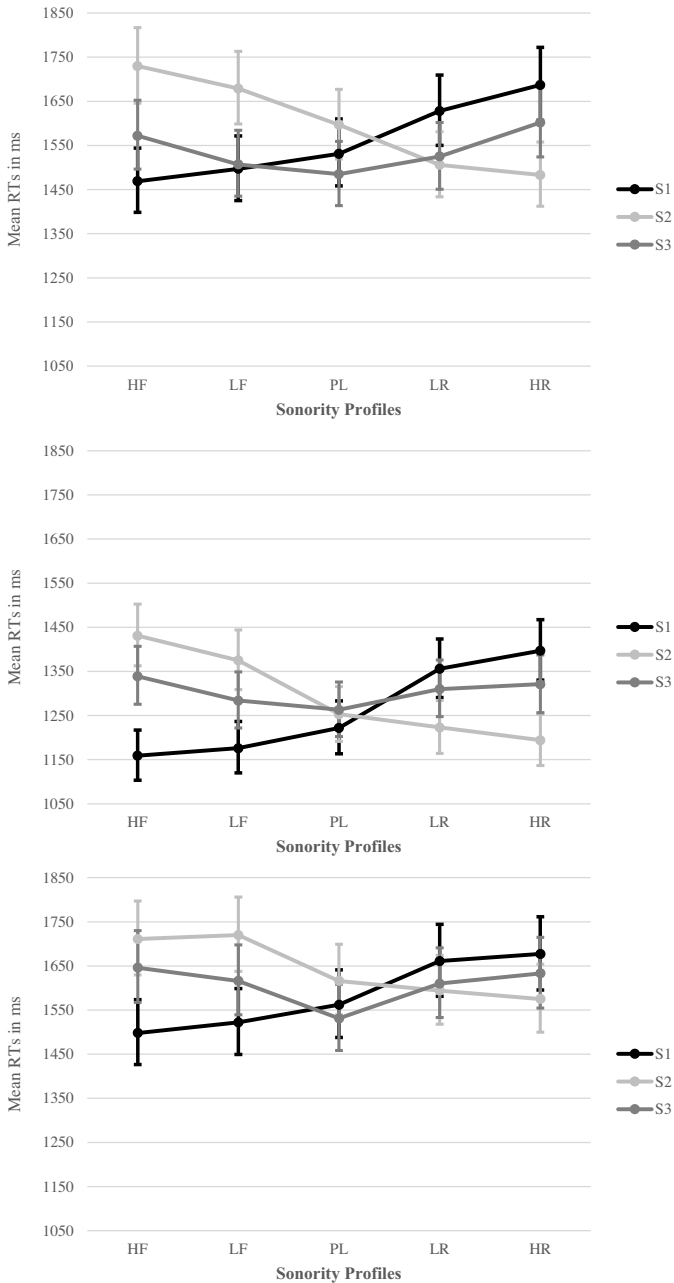


Figure 2. Mean response times (RTs) in milliseconds (ms) for the GROUP × SEGMENTATION × SONORITY PROFILE interaction with the “no” responses (pseudowords; bars represent 95% confidence intervals [CI]; upper panel: DYS children, middle panel: CA peers, and lower panel: RL peers). Note. “S1” stands for $\langle V_1C_1C_2V_2 \rangle$ segmentation, “S2” for $\langle V_1C_1^*C_2^*V_2 \rangle$ segmentation, and “S3” for $\langle V_1C_1C_2^*V_2 \rangle$ segmentation; “HF” is for high-fall, “LF” for low-fall, “PL” for plateau, “LR” for low-rise, and “HR” for high-rise sonority profiles.

However, there was a reverse pattern for $\langle V_1^*C_1C_2V_2 \rangle$ segmentation with systematic significant differences between both extreme SPs ($-9.58 < t_s < -5.78$, $p_s < .0001$). The difference between high-fall SPs and plateau SPs was not significant whichever GROUP ($-2.72 < t_s < -2.16$, $p_s > .1$), while the difference between plateau SPs and high-rise SP was significant in DYS children, $t(143.4) = 4.95$, $p < .0001$ and CA peers only, $t(142.0) = 6.87$, $p < .0001$ (in RL peers, $t(141.7) = 3.62$, $p > .1$).

For $\langle V_1C_1C_2^*V_2 \rangle$ segmentation, there was a decrease from high-fall SPs to plateau SPs but an increase from plateau SPs to high-rise SPs, which depicted a V-curve with no significant difference between high-fall SPs and high-rise SPs whichever GROUP ($-0.93 < t_s < 0.74$, $p_s > .1$). Although plateau SPs spiked down, there was no significant difference with high-fall SPs and high-rise SPs whichever GROUP ($2.93 < t_s < 3.71$, $p_s > .1$; $2.28 < t_s < 3.86$, $.09 > p_s > .1$, respectively).

Discussion

We investigated whether DYS children, who are diagnosed with a phonological deficit, have preserved phonological representations that allow them to use the syllables to segment and access words in silent reading. Crucially, we examined whether DYS children benefit from their phonological grammar, which involves sonority markedness constraints. More specifically, we examined their abilities to segment intervocalic $\langle C_1C_2 \rangle$ clusters across syllable boundaries when no statistical and distributional cues were available.

Our results support Hypothesis #1. DYS children are slower – but not less accurate – than CA and RL peers with either words or pseudowords. This observation accommodates our Hypothesis #2, which we validate too; DYS children – like CA and RL peers – recognize words when segmentation matches the syllable boundary (i.e., $\langle ar^*gent \rangle$) faster than when segmentation mismatches the syllable boundary (i.e., $\langle a^*rgent \rangle$ and $\langle arg^*ent \rangle$). This confirms a syllable compatibility effect and attests to the abilities of DYS children to use syllable representations to segment and access words, but rarely with rare $\langle VC \rangle$ syllables (with $\langle CV \rangle$ and $\langle CVC \rangle$ syllables in Doignon-Camus et al., 2013; Maionchi-Pino et al., 2010b). These first results do not support the degraded/under-specified (or over-specified) phonological representation hypothesis, which predicts that DYS children will be unable to access orthographic and phonological sublexical units like syllables, but rather fuel the phonological access hypothesis (Ramus & Ahissar, 2012; Ramus & Szenkovits, 2008).

Following the predominant degraded/under-specified (or over-specified) phonological representation hypothesis, this syllable compatibility effect in a task involving lexical decision echoes that observed in beginning and poor readers in Chetail and Mathey (2009a, 2013) who referred to the IAS model to account for this effect (Mathey et al., 2006). Their interpretation suggests that beginning and poor readers have imprecise, non-consolidated phonological sublexical representations at the syllable level – a context similar to but distinct from that of DYS children – which weakens the connection and activation strength between the letters and syllables. Thus, the syllable compatibility increases the activation of orthographic sublexical representations at the letter level. However, poor phonological sublexical

representations lower prelexical between-level facilitation. This, in turn, slows down activation propagation to the lexical level, triggering a within-level inhibition that underlies lexical competition. This resulted in strict syllable compatibility facilitation (with ⟨CV⟩ and ⟨CVC⟩ syllables). From our results, we discarded the hypothesis of degraded/under-specified phonological representations in DYS children to account for the syllable compatibility effect. First, their response patterns are similar to those observed in CA and RL peers who are “normal-to-good” readers and have, subsequently, built robust and dense sublexical representations that should have triggered syllable compatibility inhibition due to lexical competition. Then, despite their slowness, which could reflect a speed/accuracy trade-off and an impairment of the phonological route (Ziegler et al., 2008; 2014), DYS children exhibit close-to-perfect accuracy at recognizing words, whether in syllable compatibility or syllable incompatibility. If DYS children have degraded/under-specified orthographic and phonological sublexical representations that should impair the processing of syllable representations, this should have affected access, as well as both the quality and quantity of lexical representations (i.e., *lexical quality hypothesis*; Perfetti, 2007; Perfetti & Hart, 2002). Based on our results, this does not seem to be true. We propose that ⟨VC⟩ syllables are non-canonical phonological sublexical representations that are underrepresented in French. Hence, it reduces the stock of lexical representations, which is insufficient to trigger lexical competition. This explains both the slowness of DYS children and CA and RL peers compared to the results for ⟨CV⟩ and ⟨CVC⟩ syllables in previous studies that used a lexical decision task and the absence of orthographic and phonological syllable frequency effects. Indeed, either orthographic or phonological frequency modulates the facilitation vs. inhibition frequency effects. High-frequency orthographic and phonological syllables propagate activation quickly and strongly at each level to trigger lexical within-level inhibition. Low-frequency orthographic and phonological syllables slowly and weakly spread activation at each level, yet they prevent lexical inhibition. Furthermore, ⟨CV⟩ and ⟨CVC⟩ syllables are overrepresented in French (60% and 17%, respectively; Léon, 2011), generating more possible lexical candidates to underlie lexical inhibition than ⟨VC⟩ syllables. Here, how rare are words that begin with ⟨VC⟩ syllables may suppress syllable frequency effects.

However, the preference for the ⟨V₁C₁*C₂V₂⟩ segmentation with words may also suggest the importance of statistical and distributional orthographic properties in locating the syllable boundaries and grouping letters into syllables. As proposed by Doignon-Camus et al. (2013), DYS children have preserved abilities to parse and learn the statistical properties of letter co-occurrences via sensitivity to the bigram trough (but see Bonte et al., 2007; Gabay et al., 2015; Vandermosten et al., 2019 for impairments in tuning to statistical regularities in speech perception). Doignon-Camus et al. (2013) pointed out that syllable segmentation does exist in DYS children when both the orthographic and phonological syllable boundaries coincide (e.g., ⟨BI#/MIR⟩ or ⟨RON#/TA⟩; the hash indicates the orthographic boundary, the slash stands for the phonological boundary) but disappears to favor segmentation based on the bigram trough only (e.g., ⟨BI.M/BU⟩ or ⟨RO/N.ER⟩) suggesting a pure orthographic syllable effect. We would like to qualify this conclusion. First, the bigram trough illustrates the typological tendencies in French to disallow some intervocalic ⟨C₁C₂⟩ clusters as onset clusters, which naturally impose restrictions on

phonological representations and mechanically mark syllable boundaries. An in-depth inspection of the bigram frequency of the $\langle V_1C_1 \rangle$ clusters and the $\langle C_1C_2 \rangle$ in our words confirms a bigram trough for some – but not all ($n = 12$ [60.0%]) – words that we used whatever the database that we considered, but this does not guide the children’s segmentation strategies. Therefore, there remains an issue to understand how – and why – the $\langle V_1C_1 * C_2V_2 \rangle$ segmentation has been preferred when there was no clear bigram trough.

We validate Hypothesis #3 and #4. For the first time, we manipulated sonority markedness constraints for intervocalic $\langle C_1C_2 \rangle$ clusters which could be simultaneously marked, ill-formed SPs or unmarked, well-formed SPs for onset clusters ($\langle V_1 * C_1C_2V_2C_3V_3 \rangle$), syllable boundaries ($\langle V_1C_1 * C_2V_2C_3V_3 \rangle$), or coda clusters in silent reading ($\langle V_1C_1C_2 * V_2C_3V_3 \rangle$; but see Maïonchi-Pino et al., 2013 in speech perception). We find a clear-cut sonority projection effect, that is, a gradient-based preference of sonority markedness constraints for the intervocalic $\langle C_1C_2 \rangle$ clusters, which differs according to cued segmentation. As such, this first observation refutes a category-based preference that predicts $\langle C_1C_2 \rangle$ clusters to be perceived and processed equally regardless of the SPs because all of them are nonexistent in the language-specific phonological grammar of French (White & Chiu, 2017). Although we acknowledge the attestedness of some of our $\langle C_1C_2 \rangle$ clusters, these $\langle C_1C_2 \rangle$ clusters are rare in French, especially for children who have most likely never encountered them before, and, if attested, do exist in specific positions only (i.e., intervocalic position within words; e.g., $\langle lb \rangle$ in $\langle album \rangle$, *album*). Our analysis indicates that attestedness, which is observed in the different SPs that we designed, does not influence the gradual (dis)preference for these $\langle C_1C_2 \rangle$ clusters whatever the segmentation. Hence, we concur with the view that attestedness and well-formedness are perceived and processed differently and potentially occur at two different levels with two different time courses (Basirat et al., 2021; Hayes & White, 2013; White & Chiu, 2017). Crucially, our results indicate that the sonority projection effect does not derive from statistical and distributional cues since neither attestedness nor orthographic and phonological statistical properties of $\langle V_1C_1 \rangle$, $\langle V_1C_1C_2 \rangle$, and $\langle C_1C_2 \rangle$ clusters, which were kept to null or quasi-null values, modulate the (mis)perception of sonority markedness constraints (Berent, 2017; Berent & Lennertz, 2010). This result confirms that of previous studies in French-speaking DYS children and typically developing children (Maïonchi-Pino et al., 2012a, 2012b; Maïonchi-Pino, de Cara et al., 2015). An important issue lies in $\langle C_1C_2 \rangle$ clusters that are inequally unattested but share features with attested $\langle C_1C_2 \rangle$ clusters from which children can extract and generalize them to our $\langle C_1C_2 \rangle$ clusters (e.g., $\langle ft \rangle \rightarrow \langle st \rangle$; Hayes & Wilson, 2008), although most are featurally distant and distinct and cannot directly account for response patterns (e.g., $\langle zg \rangle$; Daland et al., 2011). If true and corollary to gradient-based preferences, this suggests that DYS children have preserved sensitivity to the featural properties of sounds to enforce phonological changes which make $\langle C_1C_2 \rangle$ clusters acceptable, indicating well-specified phonological representations and, hence, compensation from intact phonological grammar (Marshall et al., 2011; Soroli et al., 2010; Szenkovits et al., 2016).

As mentioned, DYS children – like CA and RL peers – exhibit a gradient-based preference for sonority markedness constraints for the intervocalic $\langle C_1C_2 \rangle$ clusters.

With the $\langle V_1^*C_1C_2V_2C_3V_3 \rangle$ segmentation which highlights unattested $\langle C_1C_2 \rangle$ onset clusters in French (e.g., $\langle lz \rangle$), DYS children gradually reject pseudowords faster as sonority-based markedness decreases from unmarked, well-formed ones (high-rise SPs; e.g., $\langle vl \rangle$) to marked, ill-formed $\langle C_1C_2 \rangle$ onset clusters (high-fall SPs; e.g., $\langle rz \rangle$). With the $\langle V_1C_1^*C_2V_2C_3V_3 \rangle$ segmentation which stands for the expected segmentation within $\langle C_1C_2 \rangle$ clusters that are unattested in the onset position in French, whatever the SPs that we designed, DYS children demonstrate a gradient-based preference of sonority markedness constraints that is proportionally reversed compared to the $\langle V_1^*C_1C_2V_2C_3V_3 \rangle$ segmentation; response times to reject pseudowords as words increase from marked, ill-formed $\langle C_1C_2 \rangle$ onset clusters (high-rise SPs; e.g., $\langle vl \rangle$) to unmarked, well-formed $\langle C_1C_2 \rangle$ onset clusters (high-fall SPs; e.g., $\langle rz \rangle$). Finally, with the $\langle V_1C_1C_2^*V_2C_3V_3 \rangle$ segmentation, both extreme SPs (high-fall SPs and high-rise SPs) do not differ but take longer to be rejected than plateau SPs. These *a priori* counterintuitive response patterns – native speakers generally show a preference for unmarked, well-formed SPs and phonologically repair marked, ill-formed ones (Berent et al., 2007, 2008, 2011; Berent, Lennertz, & Balaban, 2012; Dupoux et al., 2011; Tamási & Berent, 2015; Zhao & Berent, 2016) – describe a possible dual underlying processing. First, high-rise SPs for $\langle C_1C_2 \rangle$ onset clusters and high-fall SPs for intervocalic $\langle C_1C_2 \rangle$ clusters respect the sonority sequencing principle and the syllable contact law, respectively, and hence conform to the well-formedness of $\langle C_1C_2 \rangle$ clusters on which there is a sonority projection effect in their respective specific positions. After controlling and ruling out the effects of the statistical and distributional properties and attestedness of our $\langle C_1C_2 \rangle$ clusters, we suggest that this sonority-based well-formedness generates a conflictual situation that arises from two-cycle processing. The $\langle C_1C_2 \rangle$ clusters are first analyzed through phonological grammar. This allows children to quickly reject pseudowords that embed marked, ill-formed SPs. However, it engages an additional analysis of unmarked, well-formed SPs that are ambiguous through sonority-based similarities with attested, well-formed $\langle C_1C_2 \rangle$ clusters in French. This analysis advocates the *maximal onset satisfaction principle*, which maximizes the number of consonants in onset clusters, as long as it does not contradict universal and language-specific phonotactic restrictions (Spencer, 1996).

We confirm previous studies on speech perception with adult listeners (Hayes & Wilson, 2008; Ulbricht et al., 2016; White & Chiu, 2017); here, children first activate their abstract phonological grammar, which scans the sonority markedness constraints from a gradient-based analysis to determine well-formedness and then perform a lexical analysis by comparing unmarked, well-formed $\langle C_1C_2 \rangle$ clusters to plausible lexical candidates. Therefore, this slows down response times. However, if one considers that lexical analysis precedes analysis in the phonological grammar, we should have found equivalent response times regardless of the SPs – that is, no sonority projection effect – since the $\langle C_1C_2 \rangle$ clusters do not exist, in particular in onset position, and should be processed as category-based (dis)preferences. Of interest is what happens to coda clusters ($\langle V_1C_1C_2^*V_2C_3V_3 \rangle$ segmentation). Although we did not predict specific response patterns, the V-curve that depicts the delayed response times for both extreme SPs accommodates the lexical interferences that we describe. Indeed, high-fall SPs respect the sonority sequencing principle (Clements, 1990; 2009; Parker, 2012; e.g., $\langle rj \rangle$): an optimal coda should decrease

minimally from the vowel, but high-rise SPs transgress this by describing an optimal onset that should increase maximally toward the vowel. However, both forms are attested SPs in some lexical representations of French (e.g., /aʁk/, ⟨arc⟩, *bow* [close sonority] or /aʁk/, ⟨âpre⟩, *bitter* [far sonority]). The gradient-based preferences between SPs, though visible, concern those with a specific sonority distance. This is true between high-fall and plateau SPs ($s = -3/-2$) and/or high-rise SPs and plateau SPs ($s = +2/+3$); and, of course, between high-rise SPs and high-fall SPs ($s = -5/+5$), except for the ⟨V₁C₁C₂*V₂C₃V₃⟩ segmentation. Beyond this observation, neither low-fall SPs nor low-rise SPs differ from either high-fall SPs, plateau SPs, or high-rise SPs, pinpointing the importance for clusters to respect the *sonority dispersion principle*, which posits a maximal sonority distance between the onset and the vowel (Clements, 1990) and the *minimal sonority distance* (Selkirk, 1984; Zec, 2007), which stipulates an optimal sonority rise by at least x degrees from the cluster to the vowel. Therefore, low-fall and low-rise SPs are under-optimal, which may explain their intermediate status, which makes them sometimes harder, sometimes easier to perceive and process (Gierut, 2007; Marouby-Terriou & Denhière, 2002).

Conclusion

Taken together, our results straightforwardly demonstrate that DYS children behave similarly to their CA and RL peers despite being diagnosed with developmental dyslexia with impaired phonological abilities. Although we ensured cautious upstream sampling of DYS children ($M_{\text{age}} = 120.1$, $SD = 4.4$; $M_{\text{reading level}} = 92.5$, $SD = 2.9$; $M_{\text{delay}} = -27.6$, $SD = 3.7$), we observed variations in sensitivity to sonority markedness constraints and in abilities to segment words and pseudowords accordingly (as in CA and RL peers). Based on *ad hoc* correlation analysis in DYS children, there was no direct link between accuracy and reading delay ($r = .0007$, $p > .1$), but the correlation was significant between log-transformed RTs and reading delay ($r = .14$, $p < .0001$). Beyond the relative non-homogeneity within DYS children, their response patterns appear similar to those in CA and RL peers. Of course, this may be due to partial compensation by longer exposure to reading or remediation for some DYS children. This point needs further clarification. However, overall, this leads us to a threefold conclusion. First, we extended the hypothesis that all DYS children do not have degraded/under-specified (or over-specified) phonological representations (Ramus & Ahissar, 2012). We shed light on abilities to use phonological syllable representations to segment and access words through facilitation with syllable compatibility segmentation. However, we wondered whether their abilities to segment words uncontroversially denoted preserved phonological representations due to the systematic presence of a bigram trough. If this is the case, then their sensitivity to such a distributional cue attests to DYS children's preserved abilities to parse and extract orthographic properties of letter co-occurrences (Doignon-Camus et al., 2013; for a review, see Arciuli, 2018).

More importantly, we then found a gradient-based preference for the sonority markedness constraints when segmenting pseudowords. Their segmentation strategies follow a systematic sonority projection effect that resides in preferences for well-formed ⟨C₁C₂⟩ clusters but is not blind to the position of the segmentation

to dissociate either possible onset clusters, coda clusters, or syllable boundaries. Their sensitivity to the sonority-based structural properties of syllables stems from an intact phonological grammar that compensates or repairs unattested and ill-formed clusters to favor optimal segmentations even in the absence or quasi-absence of statistical and distributional properties (Berent & Lennertz, 2010; Berent et al., 2011, 2022; Maïonchi-Pino et al., 2012a, 2012b, 2020; Maïonchi-Pino, de Cara et al., 2015). Their slowness – whether in recognizing words or rejecting pseudowords that bear SPs, which make them similar to attested words – rather points to degraded access to both syllable representations and, to a lesser extent because we observe possible lexical interferences, lexical representations with under-specified phonological procedures.

We thus strengthen previous studies that claimed that if there is a phonological deficit, it does not lie in the phonological grammar, whether we consider an innate, universalist conception of the phonological grammar or the language-specific phonological grammar of French (Berent et al., 2013, 2016, 2022; Berent, Vaknin-Nusbaum et al., 2012; Maïonchi-Pino et al., 2013; Marshall et al., 2011; Soroli et al., 2010; Szenkovits et al., 2016). If there is a phonological deficit, it is rooted elsewhere, like in the phonetic-phonological processing (Bonte et al., 2007), the articulatory constraints (Hayes & White, 2013; Proctor & Walker, 2012), or in interaction with other factors that come into play in phonological processing (e.g., phonotactic transitional probabilities, frequency, etc.; Wiese et al., 2017; Wulfert et al., 2022). Further research is also needed to decipher to what extent the phonological grammar is fully or partly innate and whether a sonority-based intervention can play a role in the remediation of the phonological deficit in DYS children (Hunter, 2019).

Replication package. All research materials, data, analysis code, and instructions are freely and publicly available at: <https://osf.io/ec87z/>.

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

Notes

1 Homorganic consonants share the same place of articulation. The consensual classification is as follows: labial (i.e., /p/, /b/, /f/, /v/, and /m/), coronal (i.e., /n/, /t/, /d/, /l/, /s/, /z/, /ʃ/, and /ʒ/), and dorsal (i.e., /k/, /g/, and /ŋ/). Homorganic consonants are considered more complex than heterorganic consonants and are more likely to lead to compensating for coarticulation or delay and mistime the articulatory gesture (Jakielski, 2002). All of the other intervocalic C_1C_2 clusters that we used could have a different manner of articulation (i.e., obstruent, fricative, nasal, or liquid).

2 To discard a possible influence of the bigram trough on the preference for the $\langle V_1C_1^*C_2V_2 \rangle$ segmentation, we ran an additional analysis including the BIGRAM TROUGH as a fixed factor (absence vs. presence) but we found no significant main effect or interaction ($p_s > .1$).

3 To rule out possible effects of attestedness of some intervocalic $\langle C_1C_2 \rangle$ clusters (cf. Material) and confusability in spectral, acoustical, and gestural contrasts (Mielke, 2012), we ran an additional analysis including the ATTESTEDNESS factor (attested /lb/ vs. non-attested /vg/), the VOICING factor (voiced-voiced /zb/ vs. voiceless-voiceless /fs/), and the DIRECTION factor (forward direction /tf/ vs. backward direction /zg/ vs. neutral direction /dl/) as fixed factors but we did not observe significant main effects or interactions ($p_s > .1$).

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Appendix. List of stimuli for the words and pseudowords by sonority profiles

Words	Stimuli				
	Pseudowords				
	High-fall	Low-fall	Plateau	Low-rise	High-rise
absent	ulbyre	ifykte	ifsyke	ikfyce	ibnyje
acteur	uljybe	iftyke	ikpyce	ojmybe	izryve
alcool	umgove	izgove	ipkyte	otfyke	ojryve
alpage	ylvyde	ovgoze	otkyfe	ugjybe	udlyme
argent	ymdyve	ozbyge	otpyfe	ulryge	uvlyde
argile	yrjyde	umzyde	ovzyle	uvnyze	ygmyze
armure	yrzyve	ymjyze	ydgoze	ydvyne	ymryje
espace					
espion					
impair					
indice					
injure					
octave					
option					
orbite					
ordure					
organe					
orteil					
ultime					
urgent					

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