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Abstract
To date, the nature of the phonological deficit in developmental dyslexia is still debated. We concur with possible impairments in the representations of the universal phonological constraints that universally govern how phonemes co-occur as a source of this deficit. We were interested in whether—and how—dyslexic children have sensitivity to sonority-related markedness constraints. We tested 10 French dyslexic children compared with 20 typically developing chronological age-matched and reading level-matched controls. All were tested with two aurally administered syllable counting tasks that manipulated well-formedness of unattested consonant clusters, as determined by universal phonological sonority-related markedness constraints (onset clusters in Experiment 1; intervocalic clusters in Experiment 2). Surprisingly, dyslexic children's response patterns were similar to those in both control groups; as universal phonological sonority-related markedness increased, dyslexic children increasingly perceptually confused and phonologically repaired clusters with an illusory epenthetic vowel (e.g., /ʁəbal/). Although dyslexic children were systematically slower, like both control groups, they were influenced by universal sonority-related markedness constraints and hierarchically ranked constraints specific to French over evident acoustic–phonetic contrasts or sonority-unrelated cues. Our results are counterintuitive but innovative and compete to question an impaired universal phonological grammar because dyslexic children were found to have normal universal phonological constraints and were skilled to restore phonotactically legal syllable structures with a language-specific illusory epenthetic vowel (i.e., /ə/-like vowel). We discuss them regarding active phonological decoding and recoding processes within the framework of the optimality theory.

Kewords
Dyslexia; Phonological processing; Speech perception; Consonant sonority; Markedness; Epenthetic vowel

Introduction
Developmental dyslexia, which affects approximately 7% of school-aged children, is a genetic-based neurodevelopmental disorder that cannot be attributed to inadequate intellectual, psychological, or educational background (e.g., Lyon, Shaywitz, & Shaywitz, 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Ziegler, Perry, MaWyatt, Ladner, & Schulte-Körne, 2003). Previous studies have extensively documented that the phonological deficit, depicted as multidimensional difficulties, is the most reliable correlate of dyslexics' language disabilities that sustains the cognitive disorder (e.g., Castles & Coltheart, 2004; Ramus et al., 2003; Snowling, 2001; Ziegler & Goswami, 2005; Ziegler et al., 2008). Recent cross-linguistic studies have established that the phonological deficit tends to be a *universal* marker of reading difficulties (e.g., Goswami et al., 2011; Ziegler et al., 2010).

Although there is considerable evidence that the core deficit is phonological in developmental dyslexia, research has emphasized that there is no consensus on the origin of the phonological deficit (e.g., Ramus, 2001; Ziegler & Goswami, 2005). Over the past decades, the degraded/underspecified phonological representation hypothesis has been classically cited to account for dyslexics' phonological deficit and how it affects grapheme-to-phoneme correspondences that are essential to learn how to read (e.g., Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Scarborough, 1998, 2005; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Swan & Goswami, 1997). Although research has well documented that listeners' perceptual system early dynamically tunes (i.e., analyzes, adjusts, and learns) to speech (e.g., Kuhl, 2004; Saffran, Werker, & Werner, 2006), little is known about whether—and, if so, how—dyslexic individuals' perceptual system tunes to phonological regularities (e.g., Bonte, Poelmans, & Blomert, 2007; Szenkovits, Darma, Darcy, & Ramus, 2012). Phonological regularities are of special interest because they encompass language-specific rules that govern how, and how frequent, phonemes occur and co-occur in languages. A phonological sequence such as /mʒ/ never occurs in French and, therefore, is labeled as phonotactically illegal, whereas /pʁ/ occurs in French (e.g., 'prix' price) and is labeled as phonotactically legal. Thus, *phonological grammar* is an innovative source to portray the nature of the phonological deficit in developmental dyslexia (also see Szenkovits et al., 2012). Phonological grammar, defined as a system of hierarchically ranked violable phonological constraints that do not differ from language to language (i.e., are universal) within the optimality theory (OT) framework (Prince &

Smolensky, 2004; see also Moreton, 2002), rules the well-formedness of phonological sequences in a language. If phonological constraints are universal, how they are ranked is language specific.

In this article, we especially tap into the OT framework to test the *phonological grammar hypothesis* and further determine whether phonological representations themselves are degraded/underspecified or whether impaired phonological grammar underlies the phonological deficit in developmental dyslexia. Within the OT framework (Prince & Smolensky, 2004), the speaker needs to map an underlying form (input) onto a surface form (output). An underlying form (input) is a phonological form that is supposed to be stored in the mental lexicon, which undergoes successive constraints to be progressively mapped onto a surface form, that is, the phonetic form that is uttered (output). The surface form may be considered as a temporary form that reflects the underlying form after successfully passing through the phonological grammar constraints. However, constraints do not modify the input (underlying form) but rather select the optimal output candidate for utterance (surface form) among candidates that minimally transgress (or maximally respect) the constraints. OT depicts a system of hierarchically ranked violable constraints that do not differ from language to language; only the ranking differs from one language to another (the violable nature of the constraints is a major difference with generative grammar (Chomsky & Halle, 1968) and favors the description of children's language acquisition). Hence, from a unique underlying form, the phonetic form may vary greatly. To achieve such a mapping, three main mechanisms coparticipate in the OT framework. When speakers encounter an input, GEN (candidate generator) creates candidate outputs, whereas EVAL (harmony evaluator) selects the most harmonic output based on CON (language-specific, hierarchically ranked constraints of the universal set of constraints). To choose the most harmonic output (i.e., well-formedness), EVAL may transgress a lower level constraint if, and only if, such a transgression satisfies a higher level constraint. Thus, EVAL incurs conflicts and needs to take into account all of the hierarchically ranked constraints (e.g., avoid /ʁb/ for the benefit of /bʁ/).

Similarly, CON also concerns the syllabification and resyllabification processes. For instance, the underlying form needs to be unsyllabified (/paʁtiʁ/ in French, 'to leave'). However, through the GEN, EVAL, and CON mechanisms, an optimized syllabification is proposed, the best of which fulfills the hierarchically ranked constraints (/paʁ.tiʁ/, where the dot stands for the syllable boundary). Actually, all speakers have language-specific, hierarchically ranked constraints that progressively develop together with phonological acquisition and improve segmentation strategies (boundary location). Language acquisition and its differences across languages rely on a developmental triad: ranking, adjusting–shifting, and reranking the universal constraints to fit the language-specific ranking requirements (e.g., McCarthy, 2004). In particular, two main abstract universal phonological constraints that we tested in our study are important: the markedness and faithfulness constraints. On the one hand, markedness constraints are universal phonological restrictions that avoid ill-formed, phonotactically illegal sequences (i.e., *marked* phonological sequences; e.g., /ʁb/) and instead prefer well-formed, phonotactically legal ones (i.e., *unmarked* phonological sequences; e.g., /bʁ/). Of interest, these preferences stem from sonority, which is a hierarchically ranked acoustic–phonetic scale that refers to the sound's "loudness relative to that of other sounds with the same length, stress, and pitch" (Ladefoged, 1975, p. 221)—from high-sonority (vowels) to low-sonority phonemes (ranked from liquids and nasals) (labeled as *sonorant*) to fricatives and stops (labeled as *obstruent*) (see Fig. 1). Universally optimal syllables tend to preferentially respect an onset maximally growing in sonority toward the vowel and falling minimally to the coda (e.g., /ta/ is better than /la/, which in turn is better than /tʁa/ and /ʁta/; i.e., *sonority sequencing principle*) (e.g., Clements, 1990, 2006). However, universally optimal contact between syllables embed high-sonority coda followed by a low-sonority onset (i.e., the 'sonorant coda-obstruent onset' *sonority profile*, SP) (e.g., /kaʁ.tɔ̃/, where the dot represents the syllable boundary; i.e., *syllable contact law*) (e.g., Vennemann, 1988). Hence, OT supports the finely termed *universal phonological sonority-related markedness*; the least marked phonological syllable (i.e., onset cluster) describes a high-rise SP toward the vowel (e.g., /bʁ/, $s = +3$) whereas the most marked one describes a high-fall SP (e.g., /ʁb/, $s = -3$). Markedness increases progressively, and well-formedness decreases monotonically, as sonority distance decreases: high-rise SP (e.g., /bʁ/, $s = +3$) > low-rise SP (e.g., /bf/, $s = +1$) > plateau SP (e.g., /tp/, $s = 0$) > low-fall SP (e.g., /ft/, $s = -1$) > high-fall SP (e.g., /ʁb/, $s = -3$). Across syllable boundaries (i.e., intervocalic cluster), universal phonological sonority-related markedness exhibits a reverse pattern. Markedness increases,

and well-formedness decreases, as sonority distance increases from high-fall SP (unmarked structures; e.g., /ʁb/, *s* = –3) to high-rise SP (marked structures; e.g., /dl/, *s* = +3).

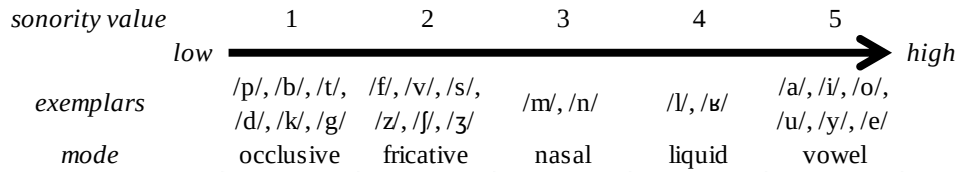

Fig. 1. Sonority scale adapted from Clements (1990).

On the other hand, faithfulness constraints are constraints that require mapping the input to the output (e.g., mapping the input /ʁb/ to the output /ʁb/). If the input is well-formed (e.g., /bʁal/), its acoustic–phonetic properties are faithfully encoded and mapped to the output /bʁ/. However, if the input is ill-formed (e.g., /ʁb/), the input fails to be faithfully encoded and mapped to the output /ʁb/ . Thus, ill-formed input is recoded as well-formed output and resyllabified to minimally violate the hierarchically ranked constraints, possibly with an illusory epenthetic vowel to lead to an optimal C–V alternation (e.g., /ʁəb/).

Previous studies have shown that adult listeners misperceived and repaired unattested C_1C_2 phonological sequences in their native language with an *illusory epenthetic vowel* proportionally to the extent that the phonological sequences differed from the universal sonority-related well-formedness either in onset clusters or in intervocalic clusters; the most ill-formed onset clusters such as /lbif/or intervocalic clusters such as /admal/ were more misperceived and repaired into /ləbif/ or /ad-əmal/, respectively, than the most well-formed ones such as /bdif/ into /bədif/ or /bnif/ into /bənif/and /abdal/ into /abədal/ or /ʒʁal/ into /ʒəʁal/, irrespective of the phonotactic transitional probabilities and articulatory or acoustic–phonetic properties of the native languages[1] (e.g., Berent, Lennertz, & Balaban, 2012; Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Berent, Lennertz, Smolensky, Vaknin-Nusbaum, 2009; Berent, Steriade, Lennertz, & Vaknin, 2007; Maïonchi-Pino et al., 2011). That is, all adult speakers have phonological grammar that relies on universal phonological sonority-related representations, which are perceptually confused and phonologically repaired with a language-specific (i.e., extracted from the target-language phoneme repertoire) illusory epenthetic vowel if the phonological sequences transgress the markedness constraints (i.e., in Japanese, a /u/-like vowel, e.g., Maïonchi-Pino et al., 2011; in English or French, a /ə/-like vowel, e.g., Berent et al., 2007, 2008; Maïonchi-Pino et al., 2011). These results are crucial because they challenge the classical view that *uncontroversially* attributed, from infants to adults, the discrimination and identification of phonological sequences to the statistical learning of phonological properties and regularities (e.g., Saffran et al., 2006).

To further pinpoint the nature of the phonological deficit, we aimed to (a) examine whether the French dyslexic children's phonological system is tuned to process finely sharpened universal phonological sonority-related markedness constraints and (b) disentangle whether children's (mis)perception and phonological repair ensue from an active phonological process that phonologically decodes and recodes the C_1C_2 clusters (e.g., Berent et al., 2012) or from a passive failure to encode and retrieve/access the acoustic–phonetic properties (e.g., Davidson, 2011). We envisaged testing whether the French dyslexic children's (mis)perception, segmentation, and phonological repair with an illusory epenthetic vowel of unattested well-formed and ill-formed phonological sequences depend on the satisfaction of universal phonological sonority-related markedness constraints (we consider as unattested C_1C_2 clusters that do not exist [i.e., are phonotactically illegal] in an initial syllable position in French; e.g., Dell, 1995). Crucially, an illusory epenthetic vowel is a phonological repair that inserts a vowel within C_1C_2 clusters to restore well-formed phonological sequences. Therefore, we designed two syllable counting tasks that compared pseudowords with unattested well-formed and ill-formed phonological sequences in onset clusters (Experiment 1) and intervocalic clusters that straddle the syllable boundaries (Experiment 2).

[1] For a counterinterpretation, see the following: in English, Davidson (2005), Davidson and Shaw (2012) and Hayes and Steriade (2004); in Japanese, Dupoux, Kakehi, Hirose, Pallier, and Mehler (1999), Dupoux, Parlato, Frota, Hirose, and Peperkamp (2011).

If the perceptual and phonological processes are rooted in the universal phonological sonority-related markedness constraints, as markedness increases, the most marked (i.e., worst ill-formed) clusters should be more misperceived and repaired than the least marked (i.e., best well-formed) clusters. That is, /ʁbal/ (high-fall sonority, the most marked) should be more misperceived as disyllabic than /pkal/ (plateau sonority), which in turn should be more misperceived than /gmal/ (high-rise sonority, the least marked) (Experiment 1). Because the markedness—and thus well-formedness—pattern is reversed within syllable boundaries, /agmal/ should be more misperceived than /apkal/, which in turn should be more misperceived than /aʁbal/ (Experiment 2). However, how dyslexic children (mis)perceive and process phonological sequences that are unattested in their native language remains an unresolved issue. In addition, it remains unspecified whether—and, if so, how—universal phonological sonority-related markedness underlies the phonological deficit in developmental dyslexia.

Here, we assume that dyslexics' phonological deficit (i.e., perception, segmentation, and repair) not only comes from degraded/underspecified phonological representations but also ensues from impaired universal phonological grammar, which degrades the phonological sonority-related markedness representations. Because adult listeners have been found to increasingly misperceive and phonologically repair C1C2 clusters, as markedness increases, with an illusory epenthetic vowel in either onset or intervocalic clusters (e.g., Maïonchi-Pino et al., 2011), we speculated the following:

1) Typically developing children (chronological age-matched and reading level-matched controls) should exhibit similar response patterns as adults, whereas dyslexic children should not be able to contrast well-formed clusters with ill-formed ones based on sonority-related markedness constraints and should equally restore unattested C_1C_2 clusters into attested C_1VC_2 ones.
2) If sonority-related markedness constraints outweigh acoustic–phonetic properties, typically developing children should follow the reverse sonority-related markedness patterns embedded in C_1C_2 intervocalic clusters, whereas dyslexic children, if oversensitive to acoustic–phonetic contrasts, should exhibit the same response patterns in both onset and intervocalic clusters (for a theoretical account, see Peperkamp, 2007).
3) If an illusory epenthetic vowel is a universal phonological repair whose nature is language specific, typically developing children as well as dyslexic children (less efficiently yet) should report an epenthetic /ə/-like vowel, which is often deleted or inserted to overcome ill-formed C_1C_2 clusters (e.g., Spinelli & Gros-Balthazard, 2007), regardless of acoustic–phonetic contexts or sonority-unrelated cues.

Method

Participants

Eligible children for this research included 10 French developmental dyslexic children with no siblings (8 boys and 2 girls, henceforth DY children) who attended a special education school that takes in children with learning disorders or a speech and language therapist's office (Rhône-Alpes region, France). DY children were assessed with a full-scale diagnosis of developmental dyslexia by a neuropsychologist. DY children did not suffer from neurological, sensory, or psychological disorders. Additional criteria were considered, including no comorbid attention deficit hyperactivity disorder (ADHD); no inadequate intellectual, psychological or educational background; a performance IQ (pIQ) above 80 (M = 97.6, SD = 2.9); and a verbal IQ (vIQ) below 110 (M = 101.4, SD = 4.3). DY children were 118 to 144 months of age (M = 130.5, SD = 8.7). DY children were enrolled in extensive reading and phonological awareness-based interventions, once a week, for less than 16 months (M = 9.6, SD = 3.9). DY children were compared with 10 chronological age-matched controls (7 boys and 3 girls, henceforth CA controls) and 10 reading level-matched controls (5 boys and 5 girls, henceforth RL controls). Both CA and RL controls were recruited from four mainstream schools located in the Rhône-Alpes region (France). Both CA and RL controls were middle socioeconomic class and monolingual native French speakers with no extensive knowledge of foreign languages (weekly second language learning did not exceed 18 months). DY children and CA and RL controls were right-handed (+0.80 and +1 right-handedness scores were measured with the Edinburgh Handedness Inventory (Oldfield, 1971)), had normal or corrected-to-normal vision, and reported no hearing disorders. Children participated after parents returned a consent form signed by both parents and children. This research received approval from the regional school management office. Pairwise Student's t tests were run to test vIQs, pIQs,

chronological ages, and reading level differences. Individual profiles and statistical results are detailed in Table 1.

Procedure

DY children, who already had vIQ and pIQ scores measured less than 9 months before this study, were individually administered the other tests in a 60-min single session. CA and RL controls were administered all of the tasks in two 90-min sessions. Children were seated in a quiet room. The procedure progressed in the following order: psychometric measures, reading tests, categorical perception task,[2] Experiment 1, and Experiment 2.

Reading tests

A 20-min French standardized age-based word reading test was used. TIMÉ 2 (Écalle, 2003) is designed for children from 72 to 96 months of age, whereas TIMÉ 3 (Écalle, 2006) is designed for children from 97 to 192 months of age. Both TIMÉ 2 and TIMÉ 3 assess orthographic and phonological knowledge level and accuracy. On the one hand, both the TIMÉ 2 and TIMÉ 3 tests were used to ensure that CA and RL controls did not experience reading disorders and had adequate reading age-based profiles. On the other hand, scores were used to match the RL controls to the DY children who were confirmed to exhibit at least 18 months of delay. TIMÉ 2 and TIMÉ 3 have fair correlations with the classical French Alouette reading test (i.e., .64 and .74, respectively (Lefavrais, 1967)). No analysis was carried out on responses.

Table 1
Chronological and reading level ages and verbal and nonverbal IQs for dyslexic children (DY), chronological age-matched controls (CA), and reading level-matched controls (RL).

Group	*N* (boys/girls)	Chronological age	Range	Reading level	PIQ	VIQ
DY children	10 (8/2)	130.5 (8.7)	9;10-12;0	108.1 (8.6)	97.6 (2.9)	104.4 (4.3)
CA controls	10 (7/3)	129.5 (8.1)	9;7-11;9	131.2 (8.5)***	109.6 (5.9)**	108.1 (4.5)*
RL controls	10 (5/5)	104.1 (8.3)***	7;11-9;11	108.8 (8.7)	102.6 (4.1)*	105.0 (6.1)

Note. Standard deviations are in parentheses. Significant difference with DY children: ***$p < .0001$; **$p < .001$; *$p < .01$. Performance IQ (pIQ) as measured by Raven's Progressive Matrices for French children (PM 38; Raven, 1998). Verbal IQ (vIQ) as measured by Wechsler Intelligence Scales for Children (WISC-III) for French children (Wechsler, 1996). Reading level as measured by TIMÉ 2 or TIMÉ 3 (Écalle, 2003, 2006).

Experiment 1

A syllable count task was used with aurally administered monosyllabic $C_1C_2VC_3$ pseudowords (e.g., /pkal/) and their disyllabic C_1/u/C_2VC_3 counterparts (e.g., /pukal/). Experimental stimuli included 20 monosyllabic $C_1C_2VC_3$ pseudowords and their disyllabic C_1/u/C_2VC_3 counterparts (see Appendix A). Pseudowords systematically shared their VC_3 rhyme (i.e., /al/) but differed in the structure of their C_1C_2 onset clusters. Homorganic consonants (i.e., consonants that share the same place of coarticulation), which are described as phonetically and articulatory more complex than heterorganic consonants (e.g., Jakielski, 2002) and notably predisposed to elicit compensation for coarticulation as well as to delay or mistime the utterance due to a greater gestural overlap (e.g., Stoet & Hommel, 1999)[3] and voice difference, were avoided within the C_1C_2 clusters (regressive/progressive voice assimilation). However, C_1 and C_2 could differ in mode of articulation (i.e., obstruent, fricative, nasal, or liquid). Onset clusters were of 5 SPs: high-fall (e.g., /ʁbal/), low-fall (e.g., /fkal/), plateau (e.g., /pkal/), low-rise (e.g., /kfal/), and high-rise (e.g., /zʁal/). Onset cluster markedness progresses from high-fall SPs (the most marked, the worst ill-formed) to high-rise SPs (the least marked, the most well-formed). Each SP contained 4 different C_1C_2 clusters. Each C_1C_2 onset cluster was repeated 8 times within each SP; overall, there were 4 C_1C_2 × 5 SPs × 8 repetitions: 160 × 2 (mono- and disyllabic pseudowords) = 320 stimuli. Disyllabic C_1/u/C_2VC_3 counterparts were uttered by a female native French speaker. All sounds were digitally recorded, sampled at a 44-kHz rate, converted with 16-bit resolution, and bandpass filtered (0–5000 Hz). Because vowels within accented syllables tend to be transformed into a schwa (i.e., /ə/) in French

[2] Detailed results of categorical perception tasks (identification and discrimination) correlated with subprofiles used in Experiments 1 and 2 (e.g., voiced vs. voiceless clusters) will be extensively presented elsewhere.

[3] We used the homorganic consonant classification 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 /ʁ/).

in unaccented syllables, we paid attention to ensure that our C_1/u/ in disyllabic pseudowords carried stress. Monosyllabic $C_1C_2VC_3$ pseudowords were obtained by splicing out step-by-step pitch periods of the /u/ with Praat software (Boersma &Weenink, 2011). Their waveforms were visually and auditorily inspected to minimize the /u/ coarticulation-based traces in the C_1 and C_2. Mean duration was 204.1 ± 12.8 ms for the C_1C_2 clusters and 98.6 ± 11.9 ms for the vowel /u/. The test was computer-driven. The script was designed, compiled, and run with E-Prime 2 Professional (Schneider, Eschman, & Zuccolotto, 2002) on Sony X-series laptop computers under Windows 7 OS. Each trial progressed as follows: a 500-ms vertically centered fixation cross (i.e., "+") was displayed and then replaced by a 200-ms blank screen and immediately followed by the sound. A 750-ms delay separated 2 consecutive trials. Children were asked to respond as quickly and accurately as possible whether the pseudowords had one or two syllables (NumPad 1 = one syllable, NumPad 2 = two syllables). Children were trained with a practice list of 16 trials with corrective feedback. No feedback was given for the experimental trials. Trials were randomized. Response times and response accuracy were recorded automatically.

Experiment 2

A syllable count task was used with aurally administered disyllabic $V_1C_1C_2VC_3$ pseudowords (e.g., /apkal/) and their trisyllabic V_1C_1/u/C_2VC_3 counterparts (e.g., /apukal/) (V_1 was always /a/). Characteristics of the pseudowords and SPs were similar to those in Experiment 1 (see Appendix B). Intervocalic cluster markedness progresses from high-rise SPs (the most marked, the worst ill-formed) to high-fall SPs (the least marked, the most well-formed). Overall, there were 4 C_1C_2 × 5 SPs × 8 repetitions: 160 × 2 (di- and trisyllabic pseudowords) = 320 stimuli. Mean duration was 195.8 ± 21.5 ms for the C_1C_2 clusters and 89.7 ± 16.7 ms for the vowel /u/. Recording, splicing, and editing processes, as well as the procedure, were similar to those in Experiment 1. Children were instructed to respond as quickly and accurately as possible whether the pseudowords had two or three syllables (NumPad 2 = two syllables, NumPad 3 = three syllables).

Results

We carried out 5 × 2 × 3 mixed-design, repeated-measures analysis of variance (ANOVA) by participant (F_1) and by item (F_2) in response times (RTs) and response accuracy (~87.5% of the data in Experiment 1; ~86.7% of the data in Experiment 2) with group (DY children, RL controls, or CA controls) as a between-participant factor and with sonority profile (high-fall, low-fall, plateau, low-rise, or high-rise) and syllable (monosyllabic or disyllabic in Experiment 1; disyllabic or trisyllabic in Experiment 2) as within-participant factors. Correct RTs were trimmed (i.e., for each participant, RTs ± 2 SD were replaced by the mean RT of each participant (2.1% of the data in Experiment 1; 2.8% of the data in Experiment 2). Descriptive data are reported in Table 2 (Experiment 1) and Table 3 (Experiment 2).

We also used *d'* to test the discrimination sensitivity thresholds and *β* to assess the criterion decision (i.e., *signal detection theory*; e.g., Macmillan & Creelman, 2005). We considered the proportion of *hit rate* (correct responses to disyllabic pseudowords in Experiment 1; correct responses to trisyllabic pseudowords in Experiment 2) and the proportion of *false alarm rate* (incorrect responses to disyllabic pseudowords in Experiment 1; incorrect responses to trisyllabic pseudowords in Experiment 2) defined in terms of standard deviate *z*-values as follows:

$$d' = z(P\left(\frac{Si}{nSi}\right)) - z(P\left(\frac{Si}{nSj}\right))$$

$$\beta = exp(d' \times \left(-\frac{1}{2} \times (z\left(P\left(\frac{Si}{nSi}\right)\right) - z\left(P\left(\frac{Si}{nSj}\right)\right)\right)\right)$$

where S_i is the number of di- or trisyllabic pseudowords, nS_i is the total number of di- or trisyllabic pseudowords, S_j is the number of mono- or disyllabic pseudowords, and nS_j is the total number of mono- or disyllabic pseudowords, so if $P(S_i,S_j) = 0$, $z = 0$, whereas if z = negative value, we used the symmetry properties of z scores as follows: $z(1 - P) = -z(P)$. If $P(S_i) = P(S_j)$, $d' = 0$ = random responses. If $P(S_i) \geq .99$ and $P(S_j) \leq .01$, ceiling effects. If $P(S_i) \leq .01$ and $P(S_j) \geq .99$, floor effects. If so, we used the transformation of P(response) as follows:

$$if\ P(Si,Sj) = 0, P(Si,Sj) = \frac{1}{2 \times n}$$

$$if\ P(Si,Sj) = 1, P(Si,Sj) = 1 - \frac{1}{2 \times n}$$

where *n* is the total number of trials.

Table 2
Mean response times in milliseconds (ms), response accuracy in percentage (%) and standard deviation (in brackets) for the unattested onset clusters to the Sonority profile × Syllable × Group (dyslexic children (DY), chronological age-matched (CA), and reading level-matched controls (RL)) in Exp. 1.

	DY children		CA controls		RL controls		*Mean*	
	monosyllabic	disyllabic	monosyllabic	disyllabic	monosyllabic	disyllabic	*monosyllabic*	*disyllabic*
High fall SP	77.8 (6.2) 1,883 (179)	93.8 (7.5) 1,444 (252)	80.3 (6.3) 1,389 (292)	95.3 (5.6) 1,133 (252)	80.3 (9.3) 1,699 (265)	95.9 (5.7) 1,175 (239)	79.5% (1,657 ms)	95.0% (1,251 ms)
Low fall SP	79.4 (7.4) 1,855 (267)	95.3 (4.7) 1,451 (347)	79.1 (7.9) 1,273 (303)	96.3 (4.1) 1,123 (209)	77.5 (7.2) 1,481 (335)	94.7 (6.9) 1,192 (243)	78.7% (1,536 ms)	95.4% (1,255 ms)
Plateau SP	83.8 (9.3) 1,692 (303)	86.6 (8.1) 1,581 (323)	87.5 (7.8) 1,267 (253)	90.3 (7.9) 1,277 (296)	85.0 (9.2) 1,310 (264)	90.9 (7.1) 1,304 (305)	85.4% (1,423 ms)	89.3% (1,387 ms)
Low rise SP	90.9 (9.6) 1,538 (285)	80.6 (6.4) 1,679 (419)	92.2 (6.8) 1,147 (150)	81.9 (8.8) 1,375 (301)	93.8 (7.4) 1,210 (202)	85.6 (9.1) 1,437 (279)	92.3% (1,299 ms)	82.7% (1,497 ms)
High rise SP	95.3 (4.7) 1,519 (329)	80.3 (8.2) 1,710 (246)	95.6 (4.2) 1,142 (146)	83.8 (7.2) 1,348 (196)	93.8 (6.3) 1,223 (178)	81.6 (6.7) 1,480 (282)	94.9% (1,295 ms)	81.9% (1,512 ms)
Mean	85.4% (1,698 ms)	87.3% (1,573 ms)	86.9% (1,244 ms)	89.5% (1,251 ms)	86.1% (1,385 ms)	89.8% (1,317 ms)		

Table 3
Mean response times (in ms), response accuracy (in %), and standard deviations (in parentheses) for the unattested intervocalic clusters to the Sonority Profile × Syllable × Group (dyslexic children [DY], chronological age-matched controls [CA], or reading level-matched controls [RL]) in Exp. 2.

	DY children		CA controls		RL controls		*Mean*	
	disyllabic	trisyllabic	disyllabic	trisyllabic	disyllabic	trisyllabic	*disyllabic*	*trisyllabic*
High fall SP	92.5 (5.1) 1,502 (253)	80.3 (10.5) 1,754 (162)	95.9 (5.1) 1,213 (191)	82.5 (8.6) 1,398 (235)	93.4 (7.4) 1,458 (241)	79.4 (9.5) 1,711 (282)	94.0% (1,391 ms)	80.7% (1,621 ms)
Low fall SP	92.5 (3.4) 1,651 (284)	83.8 (8.6) 1,771 (245)	88.4 (9.1) 1,308 (246)	84.4 (8.3) 1,382 (264)	92.2 (6.8) 1,550 (325)	77.8 (10.7) 1,558 (273)	91.0% (1,503 ms)	82.0% (1,570 ms)
Plateau SP	83.8 (8.0) 1,671 (301)	83.1 (8.4) 1,631 (215)	88.8 (7.1) 1,335 (228)	85.6 (7.4) 1,279 (176)	83.8 (6.9) 1,598 (302)	85.3 (7.8) 1,428 (265)	85.4% (1,534 ms)	84.7% (1,446 ms)
Low rise SP	82.5 (7.3) 1,810 (162)	89.4 (10.5) 1,521 (225)	86.6 (7.7) 1,391 (276)	97.5 (4.6) 1,159 (169)	85.3 (6.9) 1,704 (271)	84.4 (7.7) 1,327 (223)	84.8% (1,635 ms)	90.4% (1,336 ms)
High rise SP	77.8 (10.6) 1,868 (213)	90.9 (6.1) 1,489 (191)	82.8 (9.0) 1,474 (245)	96.9 (3.3) 1,169 (199)	78.8 (8.8) 1,692 (245)	94.4 (6.9) 1,311 (286)	79.8% (1,678 ms)	94.1% (1,323 ms)
Mean	85.8% (1,700 ms)	85.5% (1,633 ms)	88.5% (1,344 ms)	89.4% (1,277 ms)	86.7% (1,600 ms)	84.3% (1,467 ms)		

Experiment 1

Pairwise Student's *t* tests of the *d'* computed for each group did not reveal significant differences (*ps* > .10) for the discrimination sensitivity threshold among DY children ($M = 2.22 \pm 0.21$), RL controls ($M = 2.38 \pm 0.29$), and CA controls ($M = 2.41 \pm 0.27$). No child had a $d' = 0 \pm 5\%$ (i.e., random responses contained between 47.5% and 52.5%). Pairwise Student's *t* tests of β computed for each group did not reveal significant differences in the criterion decision (*ps* > .10) in DY children ($M = 0.93 \pm 0.20$), in

RL controls ($M = 0.82 \pm 0.17$), or in CA controls ($M = 0.93 \pm 0.34$). Overall, values for *d'* were ranked from very low–moderate sensitivity with difficult detection (min *d'* = 1.852, DY children No. 10) to moderate–high sensitivity with easier detection (max *d*' = 2.931, RL controls No. 8); values for β were ranked from a trend toward moderate liberalism (min $\beta = 0.527$, RL controls No. 2) to a trend toward high conservatism (max $\beta = 1.688$, CA controls No. 7).

Response times and response accuracy were correlated for monosyllabic and disyllabic pseudowords in DY children ($r = -.72$, $t(9) = -37.20$, $p < .0001$ and $r = -.70$, $t(9) = -48.26$, $p < .0001$, respectively), in RL controls ($r = -.71$, $t(9) = -37.78$, $p < .0001$ and $r = -.55$, $t(9) = -28.59$, $p < .0001$, respectively), and in CA controls ($r = -.71$, $t(9) = -28.29$, $p < .0001$ and $r = -.66$, $t(9) = -33.79$, $p < .0001$, respectively).

A main effect of group was significant in response times only, $F_1(2,27) = 55.18$, $p < .0001$, $\eta^2_p = .79$, $F_2(2,620) = 38.25$, $p < .0001$, $\eta^2_p = .55$. DY children responded slower (1635 ms) than RL controls (1351 ms, $p < .0001$) and CA controls (1247 ms, $p < .0001$). In addition, the Sonority Profile × Syllable interaction was significant in response times (Fig. 2), $F_1(4,108) = 14.25$, $p < .0001$, $\eta^2_p = .35$, $F_2(4,310) = 7.75$, $p < .0001$, $\eta^2_p = .09$, and in response accuracy, $F_1(4,108) = 66.09$, $p < .0001$, $\eta^2_p = .71$, $F_2(4,310) = 57.00$, $p < .0001$, $\eta^2_p = .69$. Fisher's LSD (least significant difference) post hoc tests (Bonferroni's adjusted α level for significance, $p < .001$) confirmed that responses were slower and less accurate as follows: high-fall SPs (e.g., /ʁbal/, the slowest and least accurate) < plateau SPs (e.g., /pkal/) < high-rise SPs (e.g., /gmal/, the fastest and most accurate) as well as low-fall SPs (e.g., /fkal/) < low-rise SPs (e.g., /kfal/). Responses to disyllabic counterparts inverted as follows: high-fall SPs (e.g., /ʁubal/) > plateau SPs (e.g., /pukal/) > high-rise SPs (e.g., /gumal/) as well as low-fall SPs (e.g., /fukal/) > low-rise SPs (e.g., /kufal/). The three-way Sonority Profile × Syllable × Group interaction did not significantly interact for response times (*Fs* < 1, *ps* > .10) or response accuracy (*Fs* < 1, *ps* > .10).

Experiment 2

A pairwise Student's *t* test of the *d'* computed for each group did not show significant differences (*ps* > .10) for the discrimination sensitivity threshold among DY children ($M = 2.19 \pm 0.33$), RL controls ($M = 2.16 \pm 0.28$), and CA controls ($M = 2.50 \pm 0.31$). No child had a $d' = 0 \pm 5\%$ (i.e., random responses contained between 47.5% and 52.5%). Pairwise Student *t* tests of β computed for each group did not show significant differences in the criterion decision (*ps* > .10) in DY children ($M = 1.11 \pm 0.44$), in RL controls ($M = 1.18 \pm 0.36$), or in CA controls ($M = 1.03 \pm 0.49$). Overall, values for *d'* were ranked from very low–moderate sensitivity with difficult detection (min *d'* = 1.730, DY children No. 4) to moderate–high sensitivity with easier detection (max *d'* = 2.991, DY children No. 8); values for β were ranked from a trend toward moderate liberalism (min $\beta = 0.464$, DY children No. 1) to a trend toward high conservatism (max $\beta = 1.895$, DY children No. 7).

Response times and response accuracy were correlated for monosyllabic and disyllabic pseudowords in DY children ($r = -.65$, $t(9) = -35.84$, $p < .0001$ and $r = -.74$, $t(9) = -62.26$, $p < .0001$, respectively), in RL controls ($r = -.64$, $t(9) = -46.85$, $p < .0001$ and $r = -.63$, $t(9) = -32.30$, $p < .0001$, respectively), and in CA controls ($r = -.58$, $t(9) = -33.01$, $p < .0001$ and $r = -.61$, $t(9) = -30.76$, $p < .0001$, respectively).

A main effect of group was significant in response times only, $F_1(2, 27) = 36.51$, $p < .0001$, $\eta^2_p = .73$, $F_2(1, 310) = 80.01$, $p < .0001$, $\eta^2_p = .70$. DY children responded slower (1667 ms) than RL controls (1534 ms, $p < .004$) and CA controls (1311 ms, $p < .0001$). The Sonority Profile × Syllable interaction was significant in response times (Fig. 3), $F_1(4, 108) = 14.78$, $p < .0001$, $\eta^2_p = .35$, $F_2(4, 310) = 40.63$, $p < .0001$, $\eta^2_p = .35$, and in response accuracy, $F_1(4, 108) = 34.05$, $p < .0001$, $\eta^2_p = .56$, $F_2(4, 310) = 49.43$, $p < .0001$, $\eta^2_p = .38$. Fisher's LSD post hoc tests (Bonferroni's adjusted α level for significance, $p < .001$) showed that responses were slower and less accurate as follows: high-rise SPs (e.g., /agmal/, the slowest and least accurate) < plateau SPs (e.g., /apkal/) < high-fall SPs (e.g., /aʁbal/, the fastest and most accurate) as well as low-rise SPs (e.g., /akfal/) < low-fall SPs (e.g., /afkal/). Responses to trisyllabic counterparts inverted as follows: high-rise SPs (e.g., /agumal/) > plateau SPs (e.g., /apukal/) > high-fall SPs (e.g., /aʁubal/) as well as low-rise SPs (e.g., /akufal/) > low-fall SPs (e.g., /afukal/). The three-way Sonority Profile × Syllable × Group interaction did not significantly interact for response times (*Fs* < 1, *ps* > .10) or response accuracy (*Fs* < 1, *ps* > .10).

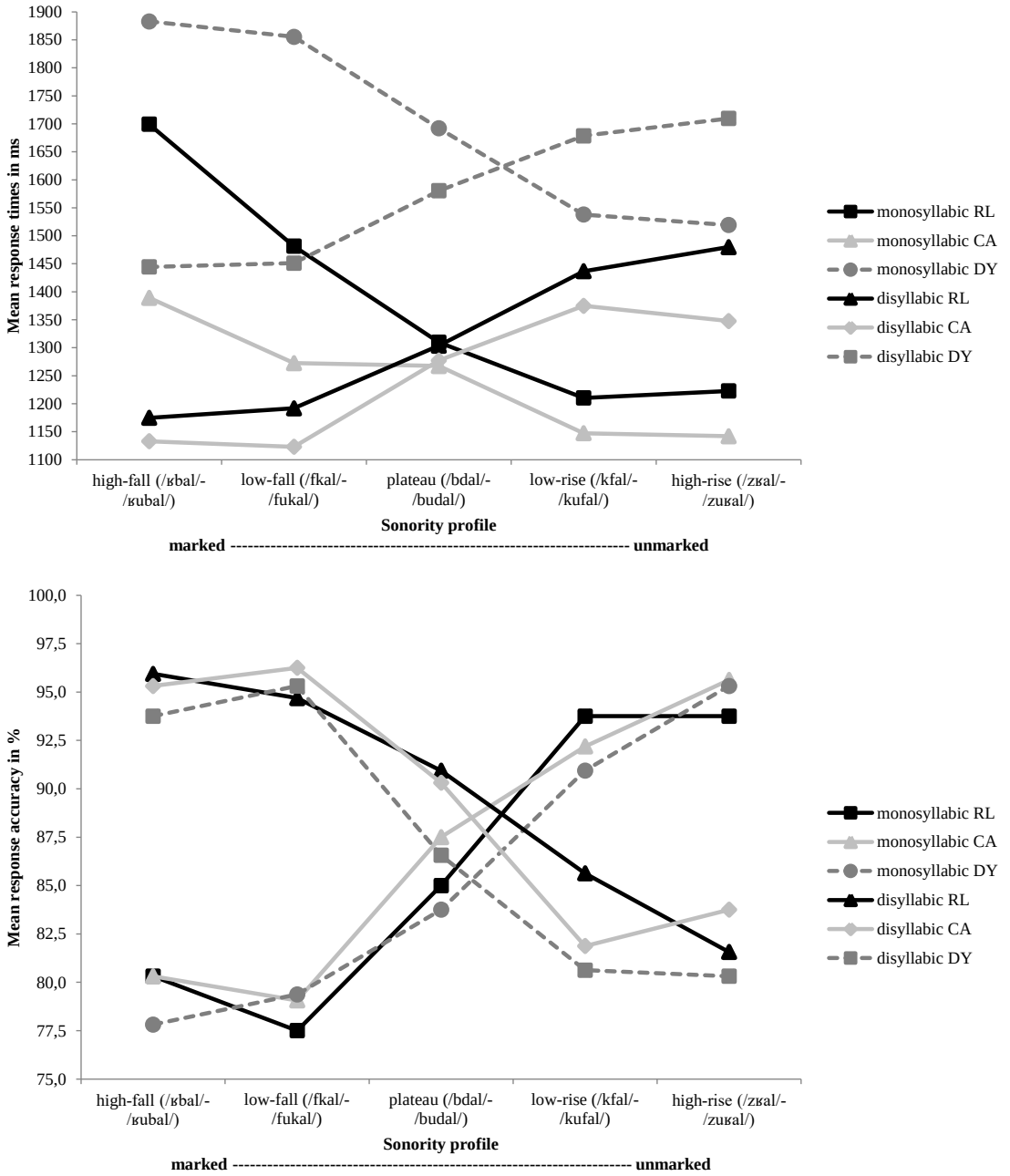

Fig. 2. Mean response times (in ms; upper panel) and mean response accuracy (in %; lower panel) for the unattested onset clusters to the Sonority Profile × Syllable interaction for group (dyslexic children [DY], chronological age-matched controls [CA], or reading level-matched controls [RL]) in Experiment 1.

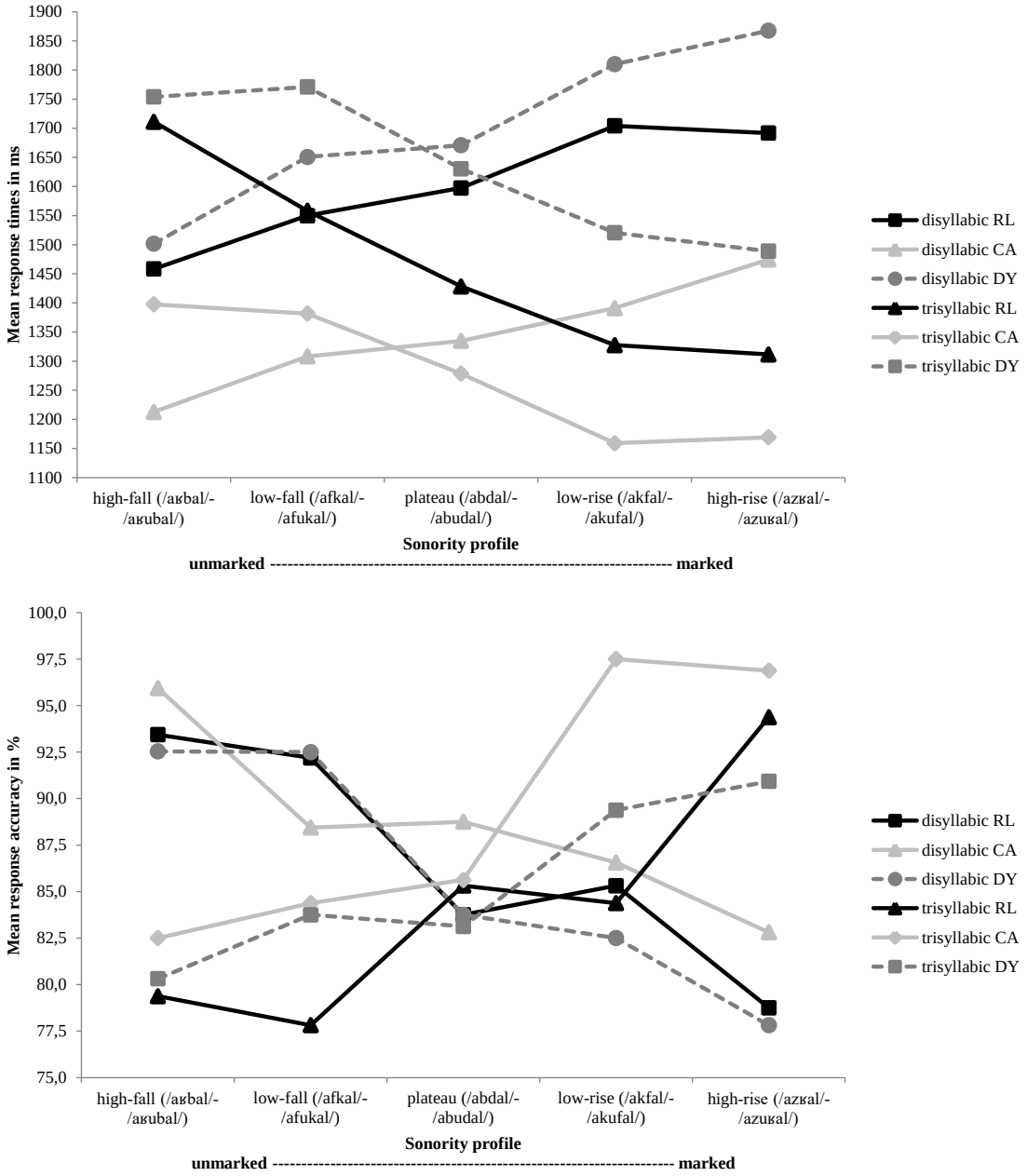

Fig. 3. Mean response times (in ms; upper panel) and mean response accuracy (in %; lower panel) for the unattested intervocalic clusters to the Sonority Profile × Syllable interaction for group (dyslexic children [DY], chronological age-matched controls [CA], or reading level-matched controls [RL]) in Experiment 2.

A posteriori measure

To ensure that misperception and repair (i.e., illusory epenthetic /ə/-like vowel) were not due to coarticulation-based artifacts relative to traces of spliced /u/ from the C_1uC_2 clusters, and to shed light on whether misperception relied on an active phonological process that phonologically decodes and recodes the C_1C_2 clusters or ensued from a passive failure to encode and retrieve the acoustic–phonetic properties, we a posteriori retested our unattested C_1C_2 clusters from both experiments.[4] All children, who were implicitly asked to count the syllables, were asked to explicitly report whether they heard a vowel and, if so, which one within our monosyllabic pseudowords (Experiment 1) and disyllabic

[4] Children were tested in both posttest sessions a few hours later. Here, we did not present the detailed comparison in response accuracy between implicit Experiments 1 and 2 and explicit posttest sessions of Experiments 1 and 2, but there is no mismatch: response patterns and response trajectories overlapped.

pseudowords (Experiment 2).[5] To shorten the tasks, each C_1C_2 cluster was repeated four times within each SP for monosyllabic pseudowords (n = 80) and disyllabic pseudowords (n = 80). Response times were not recorded. In the posttest session of Experiment 1, when children misperceived the C_1C_2 clusters (14.8%), they mostly (303/355 errors) reported an epenthetic /ə/ (M = 86.0 ± 10.5) more than an epenthetic /u/ (M = 7.9 ± 8.0), $t(58) = 31.92$, $p < .0001$, or other vowels (M = 6.1, SD = 6.6), $t(58) = 34.40$, $p < .0001$. DY children did not significantly report less epenthetic /ə/ (M = 85.6 ± 9.4) than CA controls (M = 87.1 ± 11.1, $ps > .10$) or RL controls (M = 85.4 ± 12.0, $ps > .10$). Similarly, in the posttest session of Experiment 2, when children misperceived the C_1C_2 clusters (12.6%), they mostly reported (244/303 errors) an epenthetic /ə/ (M = 81.1 ± 12.8) than an epenthetic /u/ (M = 11.4 ± 8.6), $t(58) = 24.74$, $p < .0001$, or other vowels (M = 7.6, SD = 7.6), $t(58) = 26.98$, $p < .0001$. DY children did not significantly report less epenthetic /ə/(M = 81.8 ± 6.6) than CA controls (M = 82.6 ± 15.6, $ps > .10$) or RL controls (M = 78.9 ± 15.3, $ps > .10$). In both posttest sessions, we assessed the influence of sonority profile. Neither sonority profile nor group reached the significant statistical threshold in the posttest session of Experiment 1 or Experiment 2 ($ps < .05$). However, we observed that high-fall SPs (19.6%) marginally led to more errors than plateau SPs (12.1%, $p < .06$), which in turn entailed slightly more errors than high-rise SPs (7.5%, $p < .09$, Experiment 1). Otherwise, high-rise SPs did not significantly lead to more errors (15.6%) than plateau SPs (11.5%, $p < .09$), which in turn did not entail more errors than high-fall SPs (6.5%, $p < .08$, Experiment 2).

To determine whether low-level similarities of spectral or acoustic–phonetic contrasts between sonorant consonants and vowels, which could induce more /ə/-like transitions (e.g., /ʁbal/ vs. /ʁəbal/), contribute to the misperception or repair processes, we carried out pairwise Student t tests in response accuracy (on /ə/-like vowel response only). Indeed, it has been claimed for some languages that /ə/-like vowel insertion is most likely to occur in C_1C_2 clusters in the presence of a sonorant or voiced consonants over obstruent or voiceless ones, which induce a gestural mistiming (not discussed here; e.g., Hall, 2004; see also Davidson, 2005). Hence, we needed to pay careful attention to this acoustic–phonetic context. Furthermore, if C_1C_2 clusters that contain a sonorant consonant elicit /ə/-like vowel insertion, C_1C_2 clusters must not be homorganic. In both posttest sessions, C_1C_2 clusters that embedded a sonorant consonant in either the C_1 or C_2 position (i.e., /l/, /ʁ/, or /m/), which we found in high-fall SPs (e.g., /ʁz/), low-fall SPs (e.g., /mʒ/), and high-rise SPs (e.g., /ʒʁ/), were compared with other C_1C_2 clusters (e.g., /bd/). In the posttest session of Experiment 1, sonorant-bearing C_1C_2 clusters did not significantly increase or decrease the report of an epenthetic /ə/-like vowel (86.3% vs. 88.3%). More specific, DY children (86.9% vs. 88.4%) did not significantly differ from CA controls (87.2% vs. 89.1%, $ps > .10$) and RL controls (84.7% vs. 87.3%, $ps > .10$). In addition, voiced–voiced C_1C_2 clusters (e.g., /dv/) and voiceless–voiceless C_1C_2 clusters (e.g., /pk/) did not significantly differ (86.9% vs. 88.5%, respectively, $p > .10$). DY children (87.3% vs. 88.8%) did not significantly differ from CA controls (87.5% vs. 90.0%, $ps > .10$) and RL controls (85.9% vs. 86.7%, $ps > .10$). In the posttest session of Experiment 2, sonorant-bearing C_1C_2 clusters did not significantly increase or decrease the report of an epenthetic /E/-like vowel (86.3% vs. 84.3%). In the posttest session of Experiment 2, sonorant-bearing C_1C_2 clusters did not significantly increase or decrease the report of an epenthetic /ə/-like vowel (89.4% vs. 90.2%). More specific, DY children (88.6% vs. 88.4%) did not significantly differ from CA controls (90.8% vs. 91.4%, $ps > .10$) and RL controls (88.6% vs. 90.9%, $ps > .10$). Again, voiced–voiced C_1C_2 clusters (e.g., /dv/) and voiceless–voiceless C_1C_2 clusters (e.g., /pk/) did not significantly differ (89.2% vs. 91.3%, respectively, $p > .10$). DY children (88.0% vs. 89.6%) did not significantly differ from CA controls (90.5% vs. 92.5%, $ps > .10$) and RL controls (89.1% vs. 91.7%, $ps > .10$). Finally, we also compared place of articulation within C_1C_2 clusters, that is, the forward direction (from anterior to posterior regions; e.g., /ʒg/) to backward direction (from posterior to anterior regions; e.g., /kf/). We neither observed a significant influence of direction in C_1C_2 cluster in the posttest session of Experiment 1 (87.1% vs. 87.7%, respectively) nor observed one in the posttest session of Experiment 2 (88.8% vs. 90.9%, respectively, $ps > .10$).

Linear hierarchically forced stepwise regression analyses were run in children's response accuracy to test the language-specific cues in both posttest sessions. Cluster length (in ms) was forced in Step 1, followed by biphone frequency in Step 2 (Peereman, Lété, & Sprenger-Charolles, 2007), triphone

[5] The tasks were quite similar except that for each error visual feedback was displayed, and so children were asked to press on the vowel they thought they heard (i.e., /a/, /i/, /u/, /o/, /e/, /ɛ/, /y/, /ə/, or not a vowel).

frequency in Step 3 (Gendrot, 2011) (we used C_1VC_2 triphones with a vowel /ə/, which is the most reported epenthetic vowel in French; e.g., /gm/–/gəm/), bigram frequency in Step 4 (Peereman et al., 2007), phonotactic transitional probabilities of the C_1C_2 clusters in Step 5 (Crouzet, 2000), and markedness, as determined by sonority difference, Step 6. Briefly, misperception of the C_1C_2 clusters was not due to language-specific statistical cues but rather was due to markedness for significant unique variance in both posttest sessions. Results are reported in Table 4.

Table 4
Linear stepwise regression analyses in the response accuracy to monosyllabic pseudowords of Experiment 1 with hierarchically forced entries of predictors in the posttest session of Experiment 1 (upper table) and in the posttest session of Experiment 2 (lower table).

	Step	Predictor	R^2	Adjusted R^2	R^2 change	*F* change	*p* -level	*β*
unattested clusters (onset position)	1	cluster length (ms)	.01	.001	.01	< 1	*ns*	-.10
	2	biphone frequency	.03	.002	.02	1.377	*ns*	-.13
	3	triphone frequency (/ə/-inserted)	.12	.084	.09	7.851	.006	.33
	4	phonotactic transitional probabilities	.17	.123	.05	4.452	.04	.29
	5	bigram frequency	.17	.112	.00	< 1	*ns*	.11
	6	markedness (sonority distance)	.58	.541	.41	70.190	.0001	.83

	Step	Predictor	R^2	Adjusted R^2	R^2 change	*F* change	*p* -level	*β*
unattested clusters (intervocalic position)	1	cluster length (ms)	.01	.002	.01	< 1	*ns*	.10
	2	biphone frequency	.09	.062	.08	6.351	.01	.28
	3	triphone frequency (/ə/-inserted)	.11	.075	.02	2.060	*ns*	-.17
	4	phonotactic transitional probabilities	.36	.323	.25	28.818	.0001	-.65
	5	bigram frequency	.36	.328	.00	< 1	*ns*	.50
	6	markedness (sonority distance)	.62	.589	.26	49.685	.0001	-.66

General discussion

This research investigated whether impairments in the representations of the phonological constraints that universally govern how phonemes co-occur are a possible source of the phonological deficit in developmental dyslexia. Two syllable counting tasks were aurally administered to French dyslexic children compared with chronological age-matched and reading level-matched controls. We tested whether—and how—dyslexic children had normal universal phonological grammar to (mis)perceive, segment, and repair unattested well-informed and ill-formed C_1C_2 clusters, in either onset clusters (i.e., Experiment 1; e.g., /ʁbal/) or intervocalic clusters (i.e., Experiment 2; e.g., /aʁbal/), which could depend on either an active phonological process that phonologically decodes and re-codes the C_1C_2 clusters (e.g., Berent et al., 2012) or a passive failure to encode and retrieve/access the acoustic-phonetic properties (e.g., Davidson, 2011). If the phonological grammar was impaired, dyslexic children needed to be insensitive to the satisfaction of sonority-related markedness constraints within C_1C_2 onset and intervocalic clusters; they were not expected to misperceive and repair them efficiently into C_1VC_2 clusters (i.e., insertion of an illusory epenthetic /ə/-like vowel).

Remarkably, all of our results defied our hypotheses about dyslexics' response patterns, which overlapped those of typically developing children.[6] First, dyslexic children as well as chronological age-matched and reading level-matched controls misperceived unattested C_1C_2 clusters as phonological sonority-related markedness, and so ill-formedness increased. As markedness increased from unmarked, mostly well-formed high-rise SPs (e.g., /gmal/) to marked, worst ill-formed high-fall SPs in onset clusters (e.g., /ʁbal/), all children perceptually confused monosyllabic pseudowords as their disyllabic counter-parts. Interestingly, there was no speed-accuracy trade-off. Response accuracy and response times were negatively correlated; that is, as response accuracy decreased, response times increased. These results also comply with the universally optimal onset clusters as depicted within the sonority sequencing principle (e.g., Clements, 1990, 2006).

Second, dyslexic children as well as chronological age-matched and reading level-matched controls exhibited reverse response patterns within intervocalic clusters. Importantly, all children tended to match to the well-formedness of C_1C_2 clusters as determined by the reverse sonority-related markedness underlain by the syllable contact law (e.g., Vennemann, 1988). As markedness increased from unmarked, mostly well-formed high-fall SPs (e.g., /aʁbal/) to marked, worst ill-formed high-rise SPs (e.g., /agmal/), all children perceptually confused disyllabic pseudowords as their trisyllabic counterparts. There was

[6] Additional analyses confirmed significant statistical differences with high-rise SPs, plateau SPs, and high-fall SPs in both experiments in dyslexic children regarding the Sonority Profile × Syllable interaction.

no speed–accuracy trade-off. Response accuracy and response times were negatively correlated as in Experiment 1.

Furthermore, dyslexic children's sensitivity did not differ from that of both control groups. Their discrimination sensitivity threshold (*d'*) and criterion decision (β) were comparable to those of both chronological age-matched and reading level-matched controls. This implies that discrimination abilities (input) and decision confidence (output) in dyslexic children were as efficient as in typically developing children. As evidenced in analyses, the group factor never interacted. Descriptively speaking, Figs. 2 and 3 show that dyslexic children's response patterns were similar to those in control children. Importantly, response accuracy did not differ, whereas response times were systematically slower than in both control groups.

Third, a posteriori measures confirmed that dyslexic and control children's misperception was compensated with an illusory epenthetic vowel, possibly regardless of acoustic–phonetic contrasts, similarities of spectral and temporal cues, articulatory gestures and coarticulation-based artifacts, or sonority-unrelated characteristics.[7] Seemingly, dyslexic children were as skilled as both control groups children at exhibiting a clear-cut sensitivity to universal sonority-related markedness constraints and hierarchically ranked constraints specific to French (i.e., French phonotactic rules) and, hence, to phonologically repair C_1C_2 clusters with an epenthetic /ə/-like vowel and restore a phonologically legal syllable (e.g., /ʁəbal/). This relies on a threefold observation. On the one hand, why children underperformed /ʁb/ in onset clusters but outperformed /ʁb/ in intervocalic clusters does not seem to be primarily attributable to acoustic–phonetic contrasts or ''obvious'' spectral and temporal cues because response patterns were reversed (for justification, see Peperkamp, 2007) following sonority-related markedness over individual consonant sonority (sonorant consonant within the C_1C_2 clusters), voicing, or place of articulation direction. On the other hand, it is of interest that our results shape response patterns that occurred even though no overt output was required (we requested children to perform the tasks silently, and we paid careful attention to avoid articulatory outputs such as subvocal repetitions). Thus, response patterns sketch that universal sonority-related markedness and faithfulness constraints as described within the OT framework are not restricted to, and do not require, speech production, but they also are expressed in speech perception only (see also Berent et al., 2007, 2008, 2009). That response accuracy and response times to disyllabic or trisyllabic counterparts of worst ill-formed C_1C_2 clusters relative to most well-formed ones improve in all children agrees with Berent and colleagues (2008), who discarded that such a reverse pattern stems from difficulties in perception because it persists even though ill-formed C_1C_2 clusters were no longer present. Response patterns are expressed either in an implicit context or in an explicit one, which dismisses the passive failure to encode and retrieve/access the acoustic–phonetic or articulatory properties (for counterarguments, see Davidson, 2011). Indeed, when children were required to focus on the acoustic–phonetic details within the C_1C_2 clusters, sonority-related markedness still contrasted ill-formedness versus well-formedness to misreport an illusory epenthetic vowel. This also agrees with previous results of Berent and colleagues (e.g., 2007, 2012). Hence, we strengthen the theoretical view according to which the perceptual confusion and phonological repair might originate from the active universal phonological process that we discussed further. Finally, why marked, ill-formed clusters were misperceived is not attributable to sonority-unrelated cues in either onset or intervocalic C_1C_2 clusters. Indeed, unattested C_1C_2 clusters did not embed homorganic consonants and excluded regressive/progressive voice assimilation contexts. This is crucial because both are well-documented contexts described as marked and likely to favor dynamic perceptual attunement to the closest native acoustic–phonetic environment (e.g., perceptual assimilation or compensation for coarticulation; i.e., /dla/ > /gla/) (e.g., Hallé & Best, 2007; Hallé, Seguí, Frauenfelder, & Meunier, 1998; Viswanathan, Magnuson, & Fowler, 2010). Moreover, as shown with linear hierarchically forced stepwise regression analyses, none of the French-based statistical properties did basically affect the misperception and phonological repair process of C_1C_2 clusters. Although our results challenge the uncontroversial role of acoustic–phonetic cues and language-specific phonotactic—transitional—probabilities and show that universal constraints might upstage both of them, we neither question their respective roles nor exclude an influence of articulatory gestures, but we

[7] We thank one of the reviewers who suggested that the /ə/-like epenthetic vowel response may reflect the neutral vowel, which may be the ''most attractive way'' to overcome the difficulties that lie in ''the temporal reduction of formant transitions.'' However, in our study, there is no objective evidence that supports this assumption.

draw attention to the fact that sonority-related markedness constraints and faithfulness constraints might primarily determine syllabification and resyllabification strategies in children, even those with language learning disabilities.

Dyslexic children and control children, therefore, misperceived and repaired unattested C_1C_2 onset and intervocalic clusters proportionally to the extent they differed from the universally optimal sonority-related markedness (for similar results, see Berent et al., 2007, 2008; Maïonchi-Pino et al., 2011). This underlines how efficient and well-ranked these universal constraints are in dyslexic children who are able to transgress some to pair the input to the closest output that satisfies the French language-specific phonotactic requirements. Unexpectedly, with the most marked, worst ill-formed C_1C_2 clusters within syllable boundaries (i.e., /aʒʁal/ or /agmal/), we observed a massive miscount in /a.ʒ.ʁal/, whereas /ʒʁ/ is a possible phonotactically legal C_1C_2 onset cluster in French, which is supposed to elicit an unambiguous syllabification in /a.ʒʁal/ (for details, see Spencer, 1996). However, there was evidence for a resyllabification with the insertion of an illusory epenthetic vowel that preserved but optimized the universal well-formedness of syllables (C–V alternation; e.g., /a.ʒə.ʁal/). This is especially true with dyslexic children (22.2%) and reading level-matched controls (21.2%) (chronological age-matched controls, 17.2%). Therefore, we speculate *oversensitivity* to universal phonological sonority-related markedness transgression in children who have not achieved adjusting and ranking the language-based constraints in their phonological grammar. Accordingly, universal constraints might overstep some language-specific linguistic rules as long as they improve what is universally optimal and do not counter the language-specific constraints. Of course, we acknowledge that such an ad hoc hypothesis needs to be further investigated. Importantly, all children's faithfulness constraints prefer-entially impose an epenthetic /ə/-like vowel out of obvious behavioral and statistical evidence of the influence of acoustic–phonetic or articulatory cues. This complies with Maïonchi-Pino and colleagues' (2011) results, which indicated that French adult listeners reported an epenthetic /ə/-like vowel when they misperceived C_1C_2 clusters. This extends previous findings that an epenthesis might be a universal phonological repair whose nature is language specific (i.e., in French, /ə/-like vowel, e.g., Maïonchi-Pino et al., 2011; in Japanese, /u/-like vowel, e.g., Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Dupoux, Parlato, Frota, Hirose, & Peperkamp, 2011). However, an alternative argument, which may render our interpretation slightly more delicate, is that why children labeled the illusory epenthetic vowel as a/ə/-like vowel may represent the closest phoneme to the articulatory neutral vowel extracted from the French repertoire (e.g., Fougeron, Gendrot, & Bürki, 2007). Although we did not work on its acoustic and distributional characteristics in the current study, this remains a non-negligible aspect that we may further consider.

Taken together, our results agree with the OT framework and nonimpaired phonological grammar in dyslexic children. However, there is no clear and straightforward evidence where a phonological deficit lies in dyslexic children. Given our behavioral data, we concede that we do not have a reliable observation of the phonological representations themselves, but our results challenge that dyslexics experience degraded/underspecified phonological constraints as an uncontroversial source of the phonological deficit. Therefore, any phonological deficit does not seem to depend on OT's constraints. More specific, we outline that dyslexic children were found to be sensitive to sonority-related markedness constraints and as skilled as control children to phonologically reformat syllable structures with a language-specific illusory epenthetic vowel (i.e., /ə/-like vowel). Similarly, we assume that dyslexics' phonological deficit does not rely on failures of the input analysis through the GEN and EVAL modules because the CON module (i.e., markedness and faithfulness constraints) avoids phonotactically illegal C_1C_2 clusters and provides phonotactically legal clusters as outputs for French language.

However, a current interpretation remains available: Slower response times in dyslexic children qualify, and even discredit, an impaired universal phonological grammar to at least underpin the phonological access deficit hypothesis (e.g., Ramus & Szenkovits, 2008). Indeed, their slow response times combined with their high response accuracy and well-defined constraint-based response patterns subtend a phonological deficit that mostly ensues from inabilities to store, access, or retrieve phonological constraints and representations from long-term memory (e.g., Soroli, Szenkovits, & Ramus, 2010; Szenkovits & Ramus, 2005). However, we figured out that dyslexic children might have developed compensated or alternative phonological strategies that slow down the process that goes throughout all of the phonological constraints and improves the selection of the phonological repair with an illusory epenthetic vowel. Hence, although our results highlighted innovative insightful cues that support both a

normal universal phonological grammar and maybe the phonological access deficit, we cannot determine whether dyslexic children are developmentally deviant or developmentally delayed.

Conclusion

In this study, we have shed light on an unexplored aspect of the phonological representations in developmental dyslexia. Although we observed counterintuitive results in dyslexic children, our results are innovative in emphasizing normal phonological grammar based on two sets of constraints. What we depicted is clear-cut: Dyslexic children rely on both universal sonority-related markedness constraints and faithfulness constraints that guide the (mis)perception and phonological repair of the marked, most ill-formed C_1C_2 clusters in French with an illusory epenthetic vowel. Like both chronological age-matched and reading level-matched controls, dyslexic children conformed to the universal and French principles. Of interest, our results most likely reject the respective role of a passive failure to encode and decode the acoustic-phonetic or articulatory properties to stand for an active phonological decoding and recoding process.

Thus, our findings have important implications in pointing out that the theoretical framework depicted within the OT framework should not to be overlooked because there are still shadow zones on phonological grammar constraints' role in developmental dyslexia and in syllable-timed languages. However, extensive research needs to be carefully envisaged to further understand the source of the phonological deficit as well as how universal phonological sonority-related markedness might be actually dependent on acoustic-phonetic cues (i.e., phonetically grounded; e.g., Davidson & Shaw, 2012; Hayes & Steriade, 2004; for counterarguments, see Clements, 2006) or sonority-unrelated cues (for results that minimize the role of the phonotactic—transitional —probabilities, see Berent et al., 2007, 2008; Maïonchi-Pino et al., 2011; but see also Daland et al., 2011).

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Appendix A

List of monosyllabic pseudowords used in Experiment 1.
/ʁbal/, /ʁzal/, /lval/, /lgal/ (high-fall SP);
/fkal/, /ʒgal/, /mʒal/, /ʃpal/ (low-fall SP);
/pkal/, /tpal/, /bdal/, /vzal/ (plateau SP);
/bzal/, /tfal/, /dval/, /kfal/ (low-rise SP);
/zʁal/, /ʒʁal/, /gmal/, /dmal/ (high-rise SP).

Appendix B

List of disyllabic pseudowords used in Experiment 2.
/aʁbal/, /aʁzal/, /alval/, /algal/ (high-fall SP);
/afkal/, /aʒgal/, /amʒal/, /aʃpal/ (low-fall SP);
/apkal/, /atpal/, /abdal/, /avzal/ (plateau SP);
/abzal/, /atfal/, /adval/, /akfal/ (low-rise SP);
/azʁal/, /aʒʁal/, /agmal/, /admal/ (high-rise SP).

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