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Are French dyslexic children sensitive to consonant sonority in segmentation strategies? Preliminary evidence from a letter detection task

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Abstract

This paper aims to investigate whether – and how – consonant sonority (obstruent vs. sonorant) and status (coda vs. onset) within syllable boundaries modulate the syllable-based segmentation strategies. Here, it is questioned whether French dyslexic children, who experience acoustic-phonetic (i.e., voicing) and phonological impairments, are sensitive to an optimal ‘sonorant coda – obstruent onset’ sonority profile as a cue for a syllable-based segmentation. To examine these questions, we used a modified version of the illusory conjunction paradigm with French dyslexic children compared with both chronological age-matched and reading level-matched controls. Our results first showed that the syllable-based segmentation is developmentally constrained in visual identification: In normally reading children, it appears to progressively increase as reading skills increase. However, surprisingly, our results also showed that dyslexic children were able to use syllable-sized units. Then, data highlighted that a syllable-based segmentation in visual identification basically relies on an optimal ‘sonorant coda–obstruent onset’ sonority profile rather than on phonological and orthographic statistical properties in normally reading children as well as, surprisingly, in dyslexic children. Our results are discussed to support a sonority-modulated prelexical role of syllable-sized units in visual identification in French, even in dyslexic children who exhibited a developmentally delayed profile. We argue that dyslexic children have deficits in online phonetic-phonological processing rather than degraded or underspecified phonetic-phonological representations.

Keywords

Syllable; Sonority; Illusory conjunctions; French; Dyslexia.

Introduction

Developmental dyslexia has been classically defined as severe and long-lasting deficits in learning to read which stem from a genetic neurobiological disorder not resulting from direct physiological or psychological impairments or an inadequate intellectual or educational background (e.g., Eckert, 2004; Lyon, Shaywitz, & Shaywitz, 2003; Ramus, 2001, 2003; Shaywitz & Shaywitz, 2005; Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Ziegler & Goswami, 2005). While there is a consensus that phonological awareness plays a critical role in the acquisition of normal reading skills (e.g., Castles & Coltheart, 2004), it has been suggested that the core deficit children face is rooted in an under-specified and degraded use, or representation, of phonological information (e.g., Boada & Pennington, 2006; Elbro & Jensen, 2005; Swan & Goswami, 1997). Thus, these phonological impairments would result in multi-dimensional difficulties that, in particular, would include deficits both in explicit learning and manipulating and in the implicit memorization and retrieval processes for phonological representations (e.g., Snowling, 2001; Ziegler, Castel, Pech-Georgel, George, Alario, & Perry, 2008). It has been assumed that these phonological impairments represent the most reliable correlate of reading disabilities in dyslexics (e.g., Ramus, 2001, 2003; Ramus, Rosen, Dakin, Day, Castellote, White, & Frith, 2003). However, while previous research in French focused on French normally reading children and adults, few studies on the syllable and its statistical properties (see Colé & Sprenger-Charolles, 1999; Maïonchi-Pino, Magnan, & Écalte, 2010b), or on acoustic-phonetic features (but see Fabre & Bedoin, 2003), have been conducted with impaired-reading children. There is now considerable empirical evidence that the syllable is a functional unit underlying visual word recognition processes, especially in French normally reading adults and children (e.g., Colé, Magnan, & Grainger, 1999; Doignon & Zagar, 2005, 2006; Maïonchi-Pino, Magnan, & Écalte, 2010a). Hence, a unifying theoretical framework has been developed to account for prelexical syllable activation: The Interactive Activation model with syllables (IAS; Mathey, Zagar, Doignon, & Seigneuric, 2006), which is an extended and non-implemented version of the original Interactive Model (IA; McClelland & Rumelhart, 1981). The IAS model includes a phonological syllabically structured level that mediates visual word recognition. When a printed word is displayed, letters are activated first and activation directly spreads to the lexical level (word) via the orthographic route. From there it spreads through the sublexical level (syllables) to the lexical level via the phonological route. The IAS model postulates that activation from the letter-based level propagates to the syllable-based level according to the frequency of letter co-occurrences. Therefore, “*syllable effects are assumed to ensue from two complementary processes, a facilitatory prelexical between-level activation and an inhibitory lexical within-level activation*” (Chetail & Mathey, 2008, p. 3).

The first valuable contribution to research on syllable effects in French dyslexic children was released by Colé and Sprenger-Charolles (1999). As in Colé et al. (1999), dyslexic children were explicitly instructed to decide whether or not a printed syllable (i.e., CV or CVC) appeared at the beginning of a subsequently displayed target-word systematically sharing the three first letters but differing in initial syllable structure (i.e., CV or CVC). Their results accommodated the phonological deficit hypothesis. Dyslexic children did not exhibit a *syllable compatibility effect* which supports phonological prelexical syllable-based activation; CV and CVC syllables were not detected faster when they matched the initial structure of the target-words (i.e., ‘SO’ in ‘SO.LEIL’ *sun* or ‘SOL’ in ‘SOL.DAT’ *soldier*) than when they mismatched it (‘SO’ in ‘SOL.DAT’ or ‘SOL’ in ‘SO.LEIL’). Rather, dyslexic children exhibited a *target length effect* that reflects either an orthographic letter-by-letter processing or a phonological one-by-one phoneme-based activation; CV syllables were detected faster than CVC syllables, whatever the initial structure of the target-words (i.e., ‘SO’ in ‘SO.LEIL’ or ‘SOL.DAT’). Since dyslexic children were impaired in phonological awareness, Colé and Sprenger-Charolles (1999) discarded a phonological one-by-one phoneme-based activation as well as a prelexical syllable-based activation since dyslexic children were impaired in phonological awareness. However, they concluded that sequential processing could result from degraded or under-specified phonological representations and co-occurrences of orthographic sequences encountered through multiple and longer exposures to reading.

In further research, Maïonchi-Pino et al. (2010b) repeated the Colé and Sprenger-Charolles (1999) paradigm but addressed the issues of the initial syllable and word frequencies. Using the up-to-date Manulex-infra database (Peereman, Lété, & Sprenger-Charolles, 2007) for initial syllable frequency and the Manulex database (Lété, Sprenger-Charolles, & Colé, 2004) for word frequency,

dyslexic children were compared to chronological age-matched and reading level-matched controls. Surprisingly, the authors evidenced a syllable compatibility effect in French dyslexic children who were assessed as developmentally delayed. Meanwhile, frequency-modulated effects on phonological processing were restricted to initial syllable frequency; high-frequency syllables favored the syllable compatibility effect (as they did in chronological age-matched and reading level-matched controls), whereas low-frequency syllables favored the target length effect interpreted as a phonological phoneme-based activation (as they did in reading level-matched controls; otherwise, chronological age-matched controls exhibited a syllable compatibility effect). Notably, Maïonchi-Pino et al. (2010b) showed facilitatory phonological syllable-based processing in dyslexic children for high-frequency syllables. This effect was counter-intuitive. The results reported in the literature argued that high-frequency syllables have inhibitory effects whereas low-frequency syllables have facilitatory effects (e.g., Chetail & Mathey, 2008, 2009a, 2009b). Actually, the IAS model (Mathey et al., 2006) proposed that when a printed word is displayed, a syllable activates its syllabic neighbors via prelexical between-level facilitation and activates a cohort of lexical competitors via lexical within-level inhibition. Hence, if facilitation is stronger than inhibition, lexical decision benefits from a facilitatory syllable effect, whereas, in the opposite case, an inhibitory syllable frequency effect hinders the lexical decision. Facing these unexpected results, Maïonchi-Pino et al. (2010b, p. 145) hypothesized that “*children might store the high-frequency syllables they have encountered as precompiled articulatory gestures developed through subvocal repetition and reading exposures*”. However, previous research has shown that frequency-modulated prelexical syllable effects – facilitatory or inhibitory – occur in adults as well as in normally reading children from short-duration exposures to printed stimuli (e.g., Chetail & Mathey, 2008, 2009a, 2009b) as, for instance, in the illusory conjunction paradigm (e.g., Doignon & Zagar, 2005, 2006; Doignon-Camus, Bonnefond, Touzalin-Chretien, & Dufour, 2009; Doignon-Camus, Zagar, & Mathey, 2009).

As evidenced by Doignon and Zagar (2006), in French children, phoneme associations within syllable boundaries crucially underpin syllable effects. More specifically, phoneme associations are ruled by acoustic-phonetic aspects, especially *consonant sonority*, which is the property of a sound’s “[...] *loudness relative to that of other sounds with the same length, stress, and pitch*” (Ladefoged, 1975, p. 221). Hence, consonant sonority ranks consonants from high-sonority phonemes (themselves ranked from liquids and nasals-classified as *sonorant*) to low-sonority phonemes (themselves ranked from fricatives to stops-classified as *obstruent*). A straightforward linguistic principle on phoneme associations relies on the *sonority sequencing principle* (Clements, 1990), which holds that syllables tend to preferentially respect a syllable contour with an onset maximally growing in sonority towards the vowel and falling minimally to the coda. Thus, /tra/ or /art/ sequences are allowed, whereas /rta/ or /atr/ sequences are disallowed because these phonemes are not successively ordered to conform to the sonority sequencing principle. Similarly, /la/ is dispreferred to /ta/ in the syllable-initial position, whereas high-sonority consonants are preferred in syllables that do contain a post-vocalic consonant, a coda (/al/ is better than /at/ in the syllable-final position). Furthermore, the *syllable contact law* describes a *Sonority Profile* (henceforth SP; Murray & Vennemann, 1983) which emphasizes that the optimal contact between syllables has to embed a high-sonority coda followed by a low-sonority onset.

We wonder whether statistical properties are *sufficient* to account for syllable effects. In addition, syllable effects themselves remain far less clear in French dyslexic children. Is the syllable an early prelexical reading unit in French dyslexic children? Do other linguistic properties contribute to syllable effects in dyslexic children? Do syllable effects arise with short-duration exposures to printed stimuli in dyslexic children? These questions can be addressed by investigating the influence of acoustic-phonetic properties (i.e., consonant sonority, SP) within syllable boundaries in the segmentation strategies of French dyslexic children with a perceptually constrained paradigm such as the illusory conjunction paradigm.

While dyslexic children are known to be impaired in the processing of acoustic-phonetic features, such as voicing (e.g., categorical perception; Adlard & Hazan, 1998; Bedoin, 2003; Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Breier, Fletcher, Denton, & Gray, 2004; Dufour, Serniclaes, Sprenger-Charolles, & Démonet, 2007; Mody, Studdert-Kennedy, & Brady, 1997; Poelmans, Luts, Vandermosten, Boets, Ghesquière, & Wouters, in press; Reed, 1989; Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Vandermosten, Boets, Luts, Poelmans, Wouters, & Ghesquière, 2011; Veuillet,

Magnan, Écalte, Thai-Van, & Collet, 2007), a few previous studies were interested in acoustic-phonetic properties (e.g., voicing or sonority), which require finely-sharpened abilities, in dyslexic reading, especially in French (see Maïonchi-Pino, de Cara, Écalte, & Magnan, in press-a; Krifi, Bedoin, & Mérigot, 2003).

Of interest is that an illusory conjunction paradigm has been designed to investigate whether syllables are automatically activated for early visual word identification (e.g., Prinzmetal, Treiman, & Rho, 1986). Illusory conjunctions occur in normal subjects under conditions of high attention and perceptual demands. In this paradigm, participants are instructed to detect and report the color of a target-letter in a bicolored item displayed for a short-duration. The illusory conjunction paradigm compels the perceptual system to misperceive the color of the target-letter. Two illusory conjunction patterns coexist: illusory conjunctions that preserve the syllable boundaries (i.e., report that a target-letter 'V' is the same color as 'il' in 'AN.Vil'; upper- and lower-case letters represent two different colors whereas the dot represents the syllable boundary) and illusory conjunctions that violate the syllable boundaries (i.e., report that a target-letter 'v' is the same color as 'AN' in 'AN.vil'). Hence, if participants really perceive syllable-like units in the printed items, illusory conjunction preservation would be higher than illusory conjunction violation. Accumulated data has provided evidence for automatic and early-on prelexical activation of syllable-sized units; illusory conjunction preservation is higher than illusory conjunction violation (e.g., in English: Prinzmetal et al., 1986; Prinzmetal, Hoffman, & Vest, 1991; Rapp, 1992; in French: Doignon & Zagar, 2005, 2006; Doignon-Camus, Zagar, et al., 2009).

To our knowledge, the first contribution that tested whether consonant sonority within syllable boundaries influenced the segmentation strategies used for printed CVC.CV disyllabic pseudowords in French dyslexic children was released by Fabre and Bedoin (2003). They designed a letter detection task derived from the illusory conjunction paradigm. Displaying bicolored target-pseudowords with a fixed 66-ms duration, Fabre and Bedoin (2003) selected pseudowords with either 'sonorant coda-obstruent onset' SP (e.g., 'VUL.ti') or 'obstruent coda-obstruent onset' SP (e.g., 'VUC.ti'). Target-letters were systematically set as the codas (i.e., 'L' or 'C'). Their results did not show illusory conjunction patterns that reflect a syllable-based segmentation either in reading level-matched controls or in dyslexic children: preservation illusory conjunctions were not significantly higher than violation illusory conjunctions. However, in adults, preservation illusory conjunctions were higher than violation illusory conjunctions. With regards to consonant sonority and SP within syllable boundaries, their results evidenced sonority-modulated contrasted patterns. First, no significant statistical evidence suggested that syllable-based segmentation relied on SP. Later, adults and dyslexic children were found to be sensitive to the optimal SP within syllable boundaries (i.e., 'sonorant coda – obstruent onset'; e.g., 'VUL.ti'); violation illusory conjunctions were lower with sonorant codas than with obstruent codas. Descriptively speaking, preservation illusory conjunctions were higher with sonorant codas than with obstruent ones, and they were higher than violation illusory conjunctions with sonorant codas. However, only dyslexic children made more violation illusory conjunctions than preservation illusory conjunctions with obstruent codas (e.g., reported that 'C' was the same color as 'ti' in 'VUC.ti' more than reporting that 'C' was the same color as 'VU' in 'VUC.ti'). This is inconsistent with the optimal contact between syllables since 'CT' does not respect the syllable contact law. To conclude, Fabre and Bedoin (2003) argued that French dyslexic children's sensitivity to consonant sonority within syllable boundaries is too strict to privilege an optimum coda over an optimum onset. They transgressed the *maximal onset satisfaction principle* (e.g., Spencer, 1996) that optimally maximizes the number of consonants at the beginning of a syllable as long as the linguistic constraints of French allow the cluster to be a legal one in the word-initial position. For instance, in a $C_1V_1C_2C_3V_4$ word (e.g. 'CITRON' *lemon*), the syllable boundary is located between C_1V_1 and $C_2C_3V_4$ (i.e., 'CI.TRON'), since the 'TR' cluster is considered legal in the word-initial position. However, for a cluster that the linguistic constraints of French disallow for being illegal in the word-initial position (e.g., 'CT') syllabification straddles the intervocalic consonant sequence (e.g., 'VUC.TI').

Recently, Maïonchi-Pino, de Cara, Écalte, and Magnan (in press-b) designed a letter detection task derived from the illusory conjunction paradigm to investigate developmental (i.e., beginning, intermediate, and advanced readers) sonority-modulated segmentation effects within syllable boundaries of bicolored CVC.CVC disyllabic pseudowords (e.g., 'TOL.PUDE'). While Fabre and Bedoin (2003) selected SPs and target-letters restricted to systematic low-sonority onsets (associated

with low- or high-sonority codas) and codas as target-letters, Maïonchi-Pino et al. (in press-b) designed four possible SPs within the syllable boundaries: ‘sonorant coda–sonorant onset’, ‘sonorant coda–obstruent onset’, ‘obstruent coda–obstruent onset’, and ‘obstruent coda–sonorant onset’. Codas and onsets were used as target-letters within the syllable boundaries. Maïonchi-Pino et al. (in press-b) made a compromise and used a fixed 230-ms display of the bicolored target-pseudowords¹ in order to examine the illusory conjunctions that (1) are as similar as they can and (2) favor sonority-modulated effects; factors absent in the Fabre and Bedoin (2003) results on segmentation strategies. The results were clear: preservation illusory conjunctions (i.e., ‘TOL.Pude’ or ‘TOL.pude’ misperceived as ‘TOL.pude’) progressively increased while, simultaneously, violation illusory conjunctions (i.e., ‘TOL.pude’ misperceived as ‘TOL.Pude’ or ‘TOL.Pude’) progressively decreased from beginning to advanced readers. This first pattern revealed that the syllable is an automatic prelexical reading unit that emerges as reading skill improves. Further, all children exhibited a sonority-modulated syllable-based segmentation: in particular, preservation illusory conjunctions increased whereas violation illusory conjunctions decreased with the optimal ‘sonorant coda–obstruent onset’ SP. This conforms to both the sonority sequencing principle (Clements, 1990) and the syllable contact law (Murray & Vennemann, 1983). Sonorant codas and obstruent onsets as target-letters induced more preservation illusory conjunctions than violation illusory conjunctions, which is compatible with the statistics of CVC syllables in French (e.g., 70% of sonorant codas vs. 30% of obstruent ones; Wioland, 1985). Of interest is that the authors did not observe direct and obvious effects of either the initial syllable frequency (phonological) or the positional bigram frequencies (orthographic) that precede, straddle, and follow the syllable boundaries on syllable effects (but see Doignon & Zagar, 2005, 2006; Doignon-Camus, Bonnefond, et al., 2009; Doignon-Camus, Zagar, et al., 2009).

The present study has two objectives. First, we aim to further examine whether the syllable is an early prelexical reading unit activated in response to printed words in French dyslexic children compared to chronological age-matched and reading level-matched controls. Second, we aim to explore whether – and how – the consonant sonority (obstruent vs. sonorant) and consonant position (coda vs. onset) within syllable boundaries influences syllable-based strategies with a modified version of the temporally constrained illusory conjunction paradigm (see Maïonchi-Pino et al., in press-b). To account for sonority-modulated syllable effects, we applied the Maïonchi-Pino et al. (in press-b) method. Previously, the authors corrected three main issues. Here, we raised an additional one to be fixed; Fabre and Bedoin (2003, p. 5) justified that the absence of sonority-based segmentation in normally reading children relied on the fact that they “[...] were probably not trained enough in reading to understand the importance of phonotactic rules in organizing the string of letters [...]”. Accordingly, we compared dyslexic children to chronological age-matched and reading level-matched controls. As Maïonchi-Pino et al. (in press-a, in press-b) showed sonority-modulated syllable effects with the optimal ‘sonorant coda–obstruent onset’ SP in intermediate and advanced readers, we expected that same pattern in chronological age-matched controls, but not in dyslexic children or reading level-matched controls, as in Fabre and Bedoin (2003).

Method

Participants

Fifteen dyslexic children (DY) with no comorbid ADHD participated in the study. Children were compared to 15 chronological age-matched controls (CA) and 15 reading level-matched controls (RL) who were recruited from an urban elementary school. All children were selected after parents returned a consent form. DY children were diagnosed as dyslexics by a speech and language therapist and enrolled in pediatric hospital services dedicated to children with learning disabilities. All the children were French native speakers, middle class, right-handed and were taught reading with a mixture of analytical grapheme-to-phoneme correspondences and global procedures. They had normal or corrected-to-normal vision and no hearing disorders. Reading and IQ tests were conducted prior to the

¹ As can be found in the literature, bicolored items had display durations that varied greatly, but were on average around 200–230 ms (e.g., duration ranged from 218-to-307 ms in Doignon & Zagar, 2006; ranged from 164-to-221 ms in Doignon-Camus, Zagar et al., 2009; was fixed at 200 ms in Doignon-Camus, Bonnefond et al., 2009; was fixed at 66 ms in Fabre & Bedoin, 2003; ranged from 117-to-300 ms or was fixed at 283 ms in Prinzmetal et al., 1991; ranged from 117-to-416 ms in Prinzmetal et al., 1986).

experiment. Student *t* tests confirmed that verbal and nonverbal IQs significantly differed between DY children and CA controls, $t(28) = -3.15, p < .004$, $t(28) = -3.16, p < .004$ respectively; DY children and CA controls did not differ regarding chronological age, $p > .1$. Chronological age significantly differed between DY children and RL controls, $t(28) = 8.57, p < .0001$; neither reading level nor verbal and nonverbal IQs significantly differed, $p > .1$. Chronological age significantly differed between CA and RL controls, $t(28) = 10.11, p < .0001$ as well as verbal and nonverbal IQs, $t(28) = 2.45, p < .03$, $t(28) = 2.75, p < .01$ respectively. The study was approved by the Regional School Management Office and the Hospital. Detailed profiles are presented in Table 1.

Table 1

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

Group	N (boys/girls)	Chronological age	Range	Reading level	PIQ	VIQ
DY children	15 (10/5)	121.3 (12.2)	8;5-11;11	88.9 (4.9)	104.0 (9.0)	99.9 (9.0)
CA controls	15 (10/5)	120.9 (12.8)	8;7-12;4	136.9 (10.3)***	113.4 (7.3)**	110.1 (8.8)**
RL controls	15 (10/5)	83.8 (6.2)***	6;5-8;2	88.8 (4.7)	106.6 (6.2)	102.6 (8.1)

Note: N: number of participants; chronological and reading level ages are in months; ranges are years, months; standard deviations within parentheses; significant difference with DY children. PIQ as measured by Raven's Progressive Matrices for French children (PM 38; Raven, 1998); VIQ as measured by WISC-III for French children (Wechsler, 1996).

** $p < .004$.

*** $p < .0001$.

Word reading test

All normal-reading children individually completed a standardized French word reading test (in RL controls, TIMÉ 2, fitted to 6-to-8 years-old children; Écalé, 2003 and in CA controls, TIMÉ 3, fitted to 8-to-16 years old children; Écalé, 2006) to ensure that they did not experience reading disorders and could be compared with DY children. However, DY children were assessed with the Alouette test (Lefavrais, 1967). TIMÉ 2 (Écalé, 2003), TIMÉ 3 (Écalé, 2006) and Alouette test (Lefavrais, 1967) assess the reading accuracy and the orthographic and phonological knowledge. No analysis was conducted on responses. Scores showed expected reading age-based profiles. Student *t* tests confirmed that reading level did not significantly differ between DY children and RL controls, $p > .1$. However, reading level significantly differed between DY children and CA controls, $t(28) = -10.19, p < .0001$ and between CA and RL controls, $t(28) = -16.53, p < .0001$.

Material and design

Experimental items consisted of 24 seven-letter disyllabic pseudowords (matched on orthographic length; i.e., 7 letters; see Appendix A). All the letters within the pseudowords had regular spelling-to-sound correspondences. Disyllabic pseudowords had an initial CVC syllable structure and an intervocalic consonant cluster. Syllable boundaries were located within the intervocalic clusters (i.e., between the third and the fourth letter; e.g., 'TOL.PUDE'). Intervocalic clusters were considered as phonotactically illegal in the syllable-initial position in French (e.g., Hallé, Seguí, Frauenfelder, & Meunier, 1998; McQueen, 1998). We manipulated a 2×2 design (Coda Sonority \times Onset Sonority) for consonant sonority (sonorant vs. obstruent) within intervocalic clusters: 'sonorant coda-sonorant onset' (e.g., 'TOR.LADE'); 'sonorant coda-obstruent onset' (e.g., 'TOL.PUDE'); 'obstruent coda-sonorant onset' (e.g., 'DOT.LIRE'); 'obstruent coda-obstruent onset' (e.g., 'BIC.TADE'). Mean positional bigram frequencies were estimated with the French sublexical *Surface* database computed from the *Lexique 2* database (New, Pallier, Brysbaert, & Ferrand, 2004; see Table 2) for the bigrams that precede, straddle and follow the syllable boundaries (2536, 273 and 1947 respectively). High-frequency intervocalic clusters were found within the 'obstruent-obstruent' SP ($M = 538$) or the 'sonorant-sonorant' SP ($M = 477$), mid-frequency ones were found within the 'sonorant-obstruent' SP ($M = 75$), and low-frequency ones were found within the 'obstruent-sonorant' SP ($M = 3$). Mean positional frequencies² were estimated with the French sublexical *Manulex-infra* database (Peereman et al., 2007;

² Occurrences per million were used.

see Table 3) – that provides printed frequencies in the initial position in words for French first-to-fifth grade readers – for the initial bigrams (4404), trigrams (48) and syllables (CV:446; CVC: 22). Two colors (red vs. blue) were assigned to the first and the second syllables. First and second syllables never had the same color. In the *color-syllable match condition*, color segmentation matched the syllable-based segmentation (e.g., ‘TOL.pude’) whereas, in the *color-syllable mismatch condition*, pseudowords were segmented either before (e.g., ‘TOL.pude’) or after the intervocalic cluster (e.g., ‘TOL.Pude’). Target-letters to be detected were located within the intervocalic cluster at the border of the colored segments to prevent lateral masking and were either the third (coda) or the fourth (onset) letter (e.g., ‘l’ in ‘TOL.pude’ or ‘P’ in ‘TOL.Pude’). In the color-syllable match condition, we had violation illusory conjunctions when ‘p’ or ‘L’ in ‘TOL.pude’ was misperceived as the same color as ‘TOL’ or ‘pude’ respectively. Preservation illusory conjunctions were impossible. In the color-syllable mismatch condition, we had preservation illusory conjunctions when ‘l’ in ‘TOL.pude’ was misperceived as the same color as ‘TO’ or when ‘P’ in ‘TOL.Pude’ was misperceived as the same color as ‘ude’. Violation illusory conjunctions were impossible. Hence, each pseudoword was repeated four times: twice (coda vs. onset detection) for the color-syllable match condition and twice (coda vs. onset detection) for the color-syllable mismatch condition. Experimental conditions and target-letters were counterbalanced and randomized.

Table 2

Mean positional frequencies for bigrams that precede, straddle, and follow the syllable boundary with Lexique 2 database (New et al., 2004) for the ‘sonorant–sonorant’, ‘sonorant–obstruent’, ‘obstruent–sonorant’, and ‘obstruent–obstruent’ sonority profiles.

	sonorant-sonorant	sonorant-obstruent	obstruent-sonorant	obstruent-obstruent	Mean
Precede	4728 (2211) Range (3055-7811)	2479 (1242) Range (904-3691)	1897 (1487) Range (299-3832)	1040 (847) Range (327-2262)	2536 (1995)
Straddle	477 (523) Range (0-954)	75 (31) Range (46-103)	3 (3) Range (0-6)	538 (331) Range (236-840)	273 (377)
Follow	2539 (1492) Range (366-4129)	1163 (772) Range (314-2421)	1955 (721) Range (1346-2791)	2131 (1362) Range (1004-4818)	1947 (1179)

Note: Means based on the occurrences per million; standard deviations within parentheses.

Table 3

Mean initial bigram, trigram, CV and CVC syllable frequencies with Manulex-infra database (Peereman et al., 2007) for the ‘sonorant–sonorant’, ‘sonorant–obstruent’, ‘obstruent–sonorant’, and ‘obstruent–obstruent’ sonority profiles.

	sonorant-sonorant	sonorant-obstruent	obstruent-sonorant	obstruent-obstruent	Mean
Initial bigram	6522 (3890) Range (1863-10270)	4587 (4459) Range (437-10270)	3516 (3183) Range (437-9508)	5402 (3282) Range (1863-9508)	5007 (3664)
Initial trigram	70 (93) Range (0-218)	47 (29) Range (23-84)	16 (25) Range (0-60)	17 (33) Range (0-84)	38 (54)
Initial CV syllable	302 (127) Range (81-465)	502 (371) Range (232-1224)	593 (436) Range (81-1224)	384 (331) Range (81-981)	446 (334)
Initial CVC syllable	43 (75) Range (0-195)	28 (44) Range (0-113)	12 (23) Range (0-59)	1 (1) Range (0-2)	21 (45)

Note: Means based on the occurrences per million; standard deviations within parentheses.

Procedure

Children were individually tested in a 15-min session. We used PsyScope 1.2.5 (Cohen, MacWhinney, Flatt, & Provost, 1993) to design, compile and run the task on a Macintosh iBook laptop computer with a 60-Hz refresh rate. Children sat roughly 57 cm from the screen. Two-colored pseudowords and black-colored target-letters were typed in ‘Arial’ font in upper-case letters on a white background. Pseudowords covered roughly 2.94° of visual angle. Trials progressed as follow: a green screen-centered square was displayed for 1500 ms then replaced by a fixation cross (‘+’) for 300 ms before a screen-centered black-colored target-letter appeared for 1500 ms. Then, a two-colored pseudoword flashed during 230 ms at one of the four corners of the screen immediately replaced by a 200-ms-white

screen before a screen-centered question mark ('?') appeared and remained until the child responded. A 1000-ms-delay separated two consecutive trials. Children were instructed to report the color of the target-letter in the flashed pseudoword as quickly and as accurately as possible. Children had to press on 'blue' or 'red' response keys ('a' or 'p' keys respectively). Children were first trained with a practice list with corrective feedback. No feedback was given for the experimental trials. The software automatically recorded errors. The experimenter never intervened during the session.

Results

Statistical analyses were performed with Statistica by subject ($F1$) and by item ($F2$) on errors ($\approx 22.2\%$ of the data). Two $3 \times 2 \times 2 \times 2$ mixed-design repeated measures ANOVAs were carried out with Group (DY, CA, and RL) as between-subjects factor and Coda sonority (sonorant vs. obstruent), Onset sonority (sonorant vs. obstruent), Target-letter (coda vs. onset) and Condition (violation vs. preservation) as within-subject factors. Descriptive data are summarized in Table 4.

Table 4

Descriptive statistics for the Group (dyslexic children (DY), chronological age-matched (CA) and reading level-matched controls (RL)) \times Coda sonority \times Onset sonority \times Target-letter \times Condition interaction (violation illusory conjunctions (upper panel) and preservation illusory conjunctions (lower panel)).

	color-syllable match condition (violation illusory conjunctions)								<i>Marginal Mean</i>
	sonorant coda				obstruent coda				
	sonorant onset		obstruent onset		sonorant onset		obstruent onset		
	coda	onset	coda	onset	coda	onset	coda	onset	
DY children									
<i>M</i>	14.4	20.0	6.7	8.9	15.6	15.6	15.6	12.2	13.6
<i>SD</i>	23.5	22.2	13.8	17.7	20.4	17.2	19.4	17.2	18.9
CA controls									
<i>M</i>	14.4	17.8	8.9	1.1	17.8	18.9	20.0	16.7	14.4
<i>SD</i>	13.9	14.7	13.9	4.3	17.2	17.7	21.1	16.7	14.9
RL controls									
<i>M</i>	40.0	24.4	23.3	24.4	35.6	35.6	37.8	27.8	31.1
<i>SD</i>	21.6	19.8	21.6	24.3	23.5	21.7	23.1	24.1	22.5
	color-syllable mismatch condition (preservation illusory conjunctions)								<i>Marginal Mean</i>
	sonorant coda				obstruent coda				
	sonorant onset		obstruent onset		sonorant onset		obstruent onset		
	coda	onset	coda	onset	coda	onset	coda	onset	
DY children									
<i>M</i>	15.6	24.4	32.2	27.8	24.4	20.0	14.4	21.1	22.5
<i>SD</i>	17.2	21.7	28.5	24.1	25.9	18.0	16.5	17.2	21.1
CA controls									
<i>M</i>	27.8	28.9	32.2	41.1	24.4	36.7	21.1	32.2	30.6
<i>SD</i>	19.6	18.3	18.3	20.8	19.8	16.9	16.0	29.2	19.9
RL controls									
<i>M</i>	13.3	20.0	31.1	24.4	21.1	18.9	18.9	17.8	20.7
<i>SD</i>	14.4	23.7	22.6	25.9	19.4	17.7	13.9	19.4	19.6

We used the *signal detection theory* (Tanner & Swets, 1954) to assess the discrimination sensitivity threshold (i.e., d' criterion). We performed a Student t test on the d' computed for each group.

Results showed that the discrimination sensitivity threshold in DY children ($M = 1.98$, $SD = .90$) was higher than in RL controls ($M = 1.31$, $SD = .36$), $t(28) = 2.69$, $p < .02$. Difference was not significant between DY children and CA controls ($M = 1.53$, $SD = .33$), $p < .08$. No participant had a $d' = 0$ (i.e., random responses).

ANOVAs revealed that, overall, children made significantly more preservation illusory conjunctions (24.6%) than violation illusory conjunctions (19.7%), $F1(1, 42) = 5.46$, $p = .02$, $\eta^2_p = 0.12$, $F2(2, 80) = 14.04$, $p = .0003$, $\eta^2_p = 0.15$. However, we observed a significant Condition \times Group interaction (see Figure 1), $F1(2, 42) = 5.66$, $p = .007$, $\eta^2_p = 0.21$, $F2(2, 160) = 51.80$, $p < .0001$, $\eta^2_p = 0.39$. Fisher's LSD post hoc tests showed that the nature of illusory conjunctions (violation vs. preservation) significantly depended on the groups. All the comparisons were statistically significant ($p < .05$), except preservation illusory conjunctions in CA controls which did not significantly differ from violation illusory conjunction in RL controls and violation illusory conjunctions which did not differ between CA controls and DY children ($p > .1$).

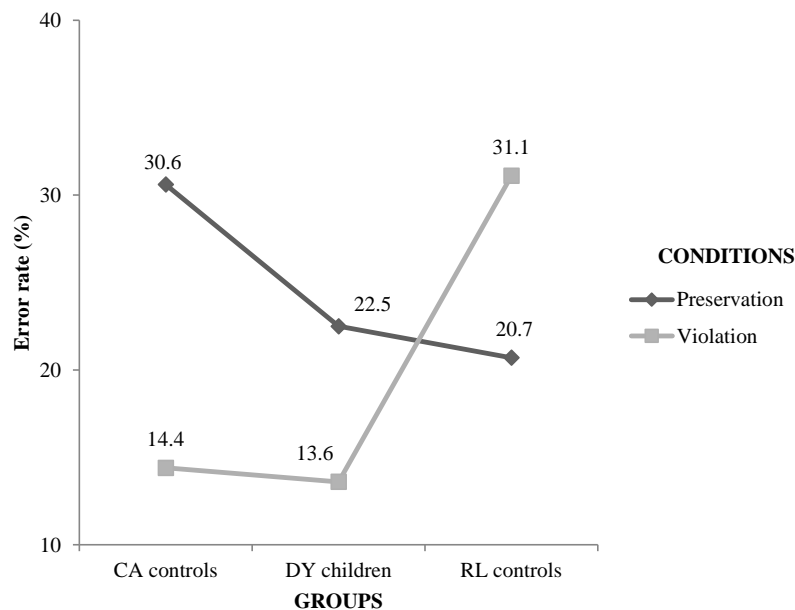


Fig. 1. Error rate (percentage; %) for the Group (dyslexic children (DY), chronological age-matched (CA) and reading level-matched controls (RL)) \times Condition interaction (violation and preservation illusory conjunctions).

Then, both the Condition \times Coda sonority and the Condition \times Onset sonority interactions were significant, $F1(1, 42) = 8.71$, $p = .005$, $\eta^2_p = 0.17$, $F2(2, 80) = 5.62$, $p = .02$, $\eta^2_p = 0.07$; $F1(1, 42) = 9.87$, $p = .003$, $\eta^2_p = 0.19$, $F2(2, 80) = 6.68$, $p = .01$, $\eta^2_p = 0.08$ respectively. Tukey's HSD post hoc tests (Bonferroni's adjusted α -level for significance, $p < .008$) revealed that violation illusory conjunctions were lower than preservation illusory conjunctions with sonorant codas (17.1% vs. 26.6%) whereas preservation illusory conjunctions were higher than violation illusory conjunctions with obstruent onsets (26.2% vs. 16.9%). Other comparisons were not significant.

Finally, the Condition \times Coda sonority \times Onset sonority interaction was significant (see Fig. 2), $F1(1, 42) = 15.05$, $p < .0001$, $\eta^2_p = 0.26$, $F2(1, 80) = 13.31$, $p = .001$, $\eta^2_p = 0.09$. Fisher's LSD post hoc tests (Bonferroni's adjusted α -level for significance, $p < .002$) showed that preservation illusory conjunctions (31.5%) were higher than violation illusory conjunctions (12.2%) for the 'sonorant-obstruent' SP. Also, children systematically made more preservation illusory conjunctions, but less violation illusory conjunctions, for the 'sonorant-obstruent' SP than any other SPs.

No other interaction was statistically significant or varied with the Group factor.

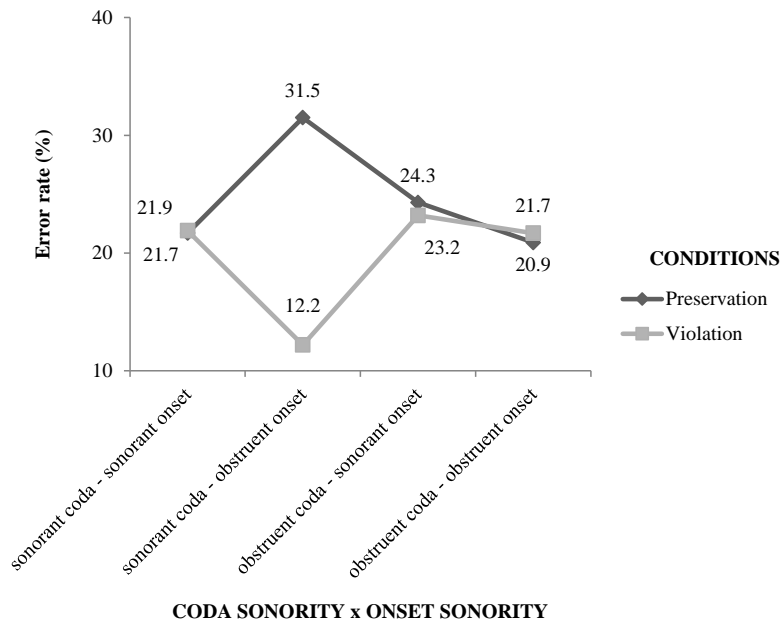


Fig. 2. Error rate (percentage; %) for the Condition (violation illusory conjunctions and preservation illusory conjunctions) × Coda sonority (sonorant and obstruent) × Onset sonority interaction (sonorant and obstruent).

Discussion

The present ongoing study was designed to investigate the nature of the sublexical units automatically evoked in French dyslexic children: is the syllable a prelexical reading unit influenced by consonant sonority (obstruent vs. sonorant) and consonant position (coda vs. onset) within syllable boundaries? A letter detection task derived from the classical illusory conjunction paradigm was administered for 4 sonority profiles (SPs): ‘sonorant coda–sonorant onset’ (e.g., ‘TOR.LADE’); ‘sonorant coda–obstruent onset’ (e.g., ‘TOL.PUDE’); ‘obstruent coda–sonorant onset’ (e.g., ‘DOT.LIRE’); ‘obstruent coda–obstruent onset’ (e.g., ‘BIC.TADE’) in DY children compared to chronological age-matched and reading level-matched controls.

Data provided three main results. First, the letter detection within the syllable boundaries did not rely on an orthographic left-to-right processing or a phonological grapheme-to-phoneme processing. We discarded both possibilities since we did not evidence that coda (i.e., third letter) or onset (fourth letter) detection differed. Across conditions, none of the children reported more target-letters as codas than target-letters as onsets. Nevertheless, we observed an asymmetry for syllable boundary processing in children’s performances. While preservation illusory conjunctions were overall higher than violation illusory conjunctions, the nature of illusory conjunctions depended on the groups. As we hypothesized, CA controls made more preservation illusory conjunctions (30.6%; e.g., ‘TOL.Pude’ or ‘Tol.pude’ misperceived as ‘TOL.pude’) than violation illusory conjunctions (14.4%; TOL.pude’ misperceived as ‘Tol.pude’ or ‘TOL.Pude’), whereas RL controls exhibited the reverse pattern; violation illusory conjunctions (31.1%) were higher than preservation illusory conjunctions (20.7%). This is consistent with previous results from Maïonchi-Pino et al. (in press-b). If our results conform to the developmental course designed for normally reading children by Seymour and Duncan (1997), who postulated that the grapho-syllabic procedure progressively becomes automatic as soon as the grapho-phonemic procedure is mastered, we outstandingly find compatible patterns with the IAS model (Mathey et al., 2006) which argues that syllable effects ensue from a prelexical mapping of orthographic graphemic representations to syllabic phonological representations. Hence, the syllable seems to be an automatic prelexical unit that is progressively available since the children exhibit clear syllable effects as reading level improves.

DY children *underperformed* CA controls but did not differ from RL controls on preservation illusory conjunctions, whereas DY children outperformed RL controls but did not differ from CA controls on violation illusory conjunctions. Most importantly, DY children made more preservation illusory conjunctions (22.5%) than violation illusory conjunctions (13.6%). Although this pattern was

not expected, since DY children were phonologically impaired, we confirmed the pattern observed in the previous results of Maïonchi-Pino et al. (2010b, in press-a). We therefore point out that, counter-intuitively, DY children were able to automatically and prelexically allocate their attention on syllable-sized units in visual identification. Our results are compatible with a finely shaded explanation. DY children may have degraded or underspecified phonological representations which could partially impair them in phonologically decoding and recoding pseudowords. However, their lower performances than CA controls for preservation illusory conjunctions, but better performances than RL controls for violation illusory conjunctions, could result from alternative compensatory phonological routines as a benefit of repetitive and long-lasting exposure to reading. This reflects that DY children could have *developmentally delayed profiles*. To confirm our interpretation, consonant sonority could help us to shed light on the syllable effects in DY children.

Of interest is that syllable effects were sonority-modulated. Consistent with our predictions, we replicated previous results with normally reading children (e.g., Fabre & Bedoin, 2003; Maïonchi-Pino, de Cara, Magnan, & Écalle, 2008, in press-a). On the one hand, children were sensitive to both the individual consonant sonority and the SPs within the syllable boundaries; first, violation illusory conjunctions were lower than preservation illusory conjunctions with sonorant codas, whereas preservation illusory conjunctions were higher than violation illusory conjunctions with obstruent onsets. Then, preservation illusory conjunctions were higher than violation illusory conjunctions for the ‘sonorant coda–obstruent onset’ optimal SP. Children made more preservation illusory conjunctions, but fewer violation illusory conjunctions, for the ‘sonorant coda–obstruent onset’ optimal SP than for any other SPs. The results are clear: children benefited from both the optimal ‘sonorant coda–obstruent onset’ SP (e.g. ‘LP’ in ‘TOL.PUDE’) and the individual consonant sonority status within syllabic boundaries. Here, our results also support previous results from Fabre and Bedoin (2003) or Maïonchi-Pino et al. (in press-a, in press-b).

We therefore claim that the syllable, and hence syllable-based segmentation strategies, is a prelexical sonority-modulated unit since syllable effects improved within a respected optimal ‘sonorant coda–obstruent onset’ SP. Surprisingly, in DY children, syllable effects were also sonority-modulated. As the analyses confirmed, differences were not skills-influenced. However, we were able to predict that the optimal ‘sonorant coda–obstruent onset’ SP could not affect DY children. To ensure that syllable effects relied on the optimal SP, as is comparable to normally reading controls, we performed a Tukey’s HSD post hoc test on the non-statistically significant Group \times Condition \times Coda sonority \times Onset sonority interaction. Again, results were clear: in DY children, preservation illusory conjunctions (30.0%) were higher than violation illusory conjunctions (7.8%) for the ‘sonorant–obstruent’ optimal SP ($p < .006$; in CA controls, $p < .0002$, in RL controls, $p > .1$). Further, unlike Fabre and Bedoin (2003), Tukey’s HSD post hoc test did not reveal that the ‘obstruent coda–obstruent onset’ SP increased preservation illusory conjunctions (17.8%) or decreased violation illusory conjunctions (19.9%) compared to any other SPs. Even if DY children were sensitive to consonant sonority within the syllable boundaries, DY children did not transgress the maximal onset satisfaction principle. We thus demonstrated that only the optimal SP within syllable boundaries underlies DY children’s syllable-based segmentation strategies. Furthermore, we emphasized the existence of a universally optimal syllable’s SP. Indeed, our results are consistent with both Clements (1990), who claimed that a syllable has to conform to an onset maximally growing in sonority towards the vowel and falling minimally to the coda, and Murray and Vennemann (1983), who described that contact between adjacent syllables has to bear a high-sonority coda – as close as possible to the preceding vowel – and a low-sonority onset. To confirm our results and disentangle some potential issues, we decided to assess whether statistical properties can account for both the syllable effects and consonant sonority in DY children.

If we refer to the statistical properties of French, syllable effects with sonorant codas and obstruent onsets are consistent with the statistical properties of consonant status within syllable boundaries. Indeed, obstruent consonants prevail in the onset position whereas sonorant consonants prevail in the coda position in CVC structures (e.g., 70% of sonorant codas vs. 30% of obstruent ones; Wioland, 1985; also see Content, Mousty, & Radeau, 1990).

Further, previous research in French showed that the syllable effects could depend on orthographic statistical properties (e.g., Chetail & Mathey, 2009b; Mathey et al., 2006). For instance, with the illusory conjunction paradigm, Doignon and Zagar (2005) found that syllable-based segmentation improved when syllable boundaries embedded low-frequency bigrams rather than high-

frequency bigrams. Their results confirmed the *bigram trough hypothesis* (e.g., Seidenberg, 1987): bigrams within the syllable boundaries are generally of a low-frequency compared to the frequency of bigrams that surround the syllable boundaries facilitating a syllable-based segmentation. However, we dismiss that the bigram frequency within syllable boundaries accounts for a syllable-based segmentation ‘sonorant coda–obstruent onset’ SP. We acknowledge that the ‘sonorant coda–obstruent onset’ SP embedded a bigram trough (see Table 2; e.g., ‘PIL.DORE’, ‘IL’ (3262), ‘LD’ (103) and ‘DO’ (314)). Similarly, although there also was a bigram trough within the ‘obstruent coda–sonorant onset’ SP (e.g., in ‘DOT.LIRE’, ‘OT’ (2455), ‘TL’ (6) and ‘LI’ (2512)) and the ‘sonorant coda–sonorant onset’ SP (e.g., in ‘TOR.LADE’, ‘UR’ (7312), ‘RL’ (954) and ‘LI’ (2791)), preservation illusory conjunctions did not increase while violation illusory conjunctions did not decrease with both SPs compared to the ‘sonorant coda–obstruent onset’ SP. Both SPs did not significantly differ. Similarly, low-frequency SPs found within the ‘obstruent coda–sonorant onset’ SP (e.g., ‘TL’ (1)), high-frequency SPs found within the ‘obstruent coda–obstruent onset’ (e.g., ‘CT’ (2595)), and the ‘sonorant coda–sonorant onset’ SPs (e.g., ‘RL’ (954)) did not significantly differ with either preservation or violation illusory conjunctions. Accordingly, we believe that the bigram trough hypothesis (Seidenberg, 1987) cannot basically account for the performances.

As is generally supported in silent reading in French (e.g., Chetail & Mathey, 2009b; Conrad, Jacobs, & Grainger, 2007; Mathey & Zagar, 2002), initial high-frequency syllables (orthographic and phonological) have inhibitory effects that are interpreted in terms of lexical competition (also see Maionchi-Pino et al., 2010a, 2010b; for counter-arguments with French children; moreover, lexical competition is not supported here). We observed that the ‘sonorant coda–sonorant onset’ SP that exhibited the highest initial trigram frequency (from 0-to-218; $M = 70$), the highest syllable frequency (from 0-to-195; $M = 43$), and the highest bigram frequency for bigrams that precede the syllable boundaries (from 3055-to-7811; $M = 4728$) neither increased preservation illusory conjunctions nor decreased violation illusory conjunctions. We also observed that the ‘obstruent coda–obstruent onset’ SP that exhibited the lowest initial trigram frequency (from 0-to-84; $M = 17$), the lowest syllable frequency (from 0-to-2; $M = 1$), and the lowest bigram frequency that preceded the syllable boundaries (from 327-to-2262; $M = 1040$) neither increased preservation illusory conjunctions nor decreased violation illusory conjunctions. With regards to our results, we propose that orthographic and phonological frequencies did not straightforwardly nor basically influence the syllable-based segmentation but could be viewed as a second-ranking factor beside the optimal ‘sonorant coda–obstruent onset’ SP.

With regards to the patterns observed in DY children, we showed that DY children have developed a language-specific sensitivity to sonority-related cues within syllable boundaries which were not primarily influenced by statistics. We hypothesize that sonority-modulated syllable effects in DY children, which were lower than in CA controls but higher than in RL controls, argues for developmentally delayed profiles. We therefore adhere to the hypothesis that dyslexics’ performances may be related to deficits in online phonetic-phonological processing rather than degraded or underspecified phonetic-phonological representations (e.g., Blomert, Mitterer, & Paffen, 2004; Bonte, Poelmans, & Blomert, 2007). This is also compatible with Ramus and Szenkovits (2008) who hypothesized that dyslexics’ deficits do not depend on degraded or underspecified phonological representations, but their deficits stem from impaired access to phonological representations.

Conclusion

Our findings evidenced three main results. First, skilled normally reading children (i.e., CA controls) are sensitive to an optimal sonority-based organization within syllable boundaries (i.e., ‘sonorant coda – obstruent onset’ SP), favoring an automatic syllable-based segmentation. As with CA controls, DY children surprisingly also exhibited sonority-modulated syllable effects restricted to the optimal ‘sonorant coda – obstruent onset’ SP, even in this task that required quick, automatic and uncontrolled processes. Finally, orthographic and phonological statistical properties did not highlight direct and systematic effects on SP preference and syllable-based segmentation. The optimal SP could be a relevant, internal organization within the syllable boundary to efficiently underlie phonological syllable-based processes, even in phonologically impaired children. We assume that DY children could extract sonority-related organization from two sources: from implicit knowledge developed through oral exposures, and also from partial orthographic knowledge of words that they have encountered.

Of importance is that our findings accommodate – and provide further arguments – to previous research on the early role of the syllable as a prelexical unit in normally reading children (e.g., Chetail & Mathey, 2008; Colé et al., 1999; Doignon & Zagar, 2006; Maionchi-Pino et al., 2010a) and also in dyslexic children (e.g., Maionchi-Pino et al., 2010b). Further research and models have to take into account syllable-sized units and consonant sonority to examine dyslexics' disorders and also to design computer-assisted learning program that focus on syllable-based segmentation in French children to improve phonological performances (e.g., Écalle, Magnan, & Calmus, 2009). Of interest is that our results could be extended, in further research, to Romance languages sharing some characteristics in common with French, such as Spanish, Italian, or Portuguese.

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Appendix A

Stimuli used in the experiment

Sonorant Coda		Obstruent Coda	
Sonorant Onset	Obstruent Onset	Sonorant Onset	Obstruent Onset
BILRATE	BULPOTE	BUDLOTE	BICTADE
BIRLOTE	PILDORE	DATLORE	BIPTADE
DALRITE	PULDITE	DOTLIRE	DACTULE
PURLIDE	TALPIDE	PIDLARE	DAPTOLE
TOLRUDE	TOLDARE	PITLUDE	DOPTILE
TORLADE	TOLPUDE	TADLITE	PUCTODE