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Is syllable segmentation developmentally constrained by consonant sonority within syllable boundaries in silent reading? Evidence in French children

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Abstract

There is agreement that French typically reading children use syllable-sized units to segment words. Although the statistical properties of the initial syllables or the clusters within syllable boundaries seem to be crucial for syllable segmentation, little is known about the role of consonant sonority in silent reading. In two experiments that used audio-visual and visual pseudoword recognition tasks with 300 French typically developing children, we showed a progressive increase in the use of syllable segmentation from the first through fifth years of reading instruction. The children were influenced both by an optimal ‘sonorant coda–obstruent onset’ sonority profile and by the individual position-dependent consonant sonority within syllable boundaries. Orthographic and phonological statistical properties did not clearly modulate the response patterns. We provide innovative data to help further understand the developmental course of the use of syllable segmentation as determined by sonority. We discuss our results in the light of linguistic principles.

Keywords

Syllable; Sonority; French; Audio-visual processing; Reading acquisition.

Introduction

Are syllable segmentation strategies developmentally constrained by consonant *sonority* (sonorant vs obstruent) and consonant position within intervocalic clusters (coda vs onset) in silent reading in French children? To date, this issue is rather unclear, and it would clearly be of interest to resolve it because French, which has more than 75 million native speakers and 190 million secondary speakers (e.g., Weber, 1997), is described as a syllable-timed language whose phonological system mostly conforms to universal linguistic principles and whose syllable structures are phonologically well formed. However, the studies that have focused on how these linguistic principles impact the segmentation strategies in reading are rare.

Most research has focused on the statistical, orthographic and phonological properties of French to account for the syllable as an early prelexical and segmental unit in reading in typically developing children (e.g., Bastien-Toniazzo, Magnan, & Bouchafa, 1999; Chetail & Mathey, 2009a, 2009b, 2013; Colé, Magnan, & Grainger, 1999; Doignon & Zagar, 2006; Doignon-Camus, Bonnefond, Touzalin-Chretien, & Dufour, 2009a; Doignon-Camus, Zagar, & Mathey, 2009b) and even also in dyslexic children (e.g., Maïonchi-Pino, Magnan, & Écalle, 2010a). Whereas these studies have revealed contrasting frequency-modulated findings, other studies have failed to find clear and straightforward evidence that the statistical regularities of letter co-occurrences modulate word parsing (e.g., Chetail & Mathey, 2008; Doignon & Zagar, 2006; Doignon-Camus et al., 2009a; Doignon-Camus, Seigneuric, Perrier, Sisti, & Zagar, 2013; Maïonchi-Pino, Magnan, & Écalle, 2010b). More importantly, almost all the associated research has, as far as we know, disregarded intrinsic acoustic-phonetic phoneme properties, such as *sonority*, which may govern how phonemes are arranged in words (Fabre & Bedoin, 2003; Maïonchi-Pino, de Cara, Écalle, & Magnan, 2012a, 2012b, 2012c).

To assess the contribution of *sonority* – and the linguistic principles it underpins – to the development of syllable segmentation strategies during reading acquisition in French typically developing children, we report data from two experiments that used (1) an audio-visual pseudoword recognition task and (2) a visual pseudoword recognition task in French children in the first to fifth years of reading acquisition.

*Sonority*¹ is described as a scalar acoustic measure of intensity with elusive phonetic correlates (e.g., Clements, 2006; Parker, 2008), which may be used to specify how phonemes and letters co-occur. Parker (2008) thus considers that sonority is a phonological property of sounds, whose acoustic intensity is the most reliable correlate, which is envisaged as a universal, formal, scalar, feature-like phonological element that categorises all speech sounds into a hierarchical acoustic-phonetic scale. For instance, French phonemes are ranked from high-sonority (vowels) to low-sonority (ranked from liquids and nasals [labelled as *sonorant*] to fricatives and stops [labelled as *obstruent*]; Figure 1). Clements (1990, 2006) describes universally optimal syllables that tend to conform to the *Sonority Sequencing Principle* (SSP henceforth), which defines the syllable's *Sonority Profile* (SP henceforth) and its well-formedness. An optimal syllable should preferably have an onset that grows maximally in sonority towards the vowel and falls minimally towards the coda. As confirmed by extensive typological surveys, well-formed syllables mostly respect the SSP, and CV syllables (i.e., consonant-vowel) are the universally optimal structures available across languages (although some languages tolerate consonant clusters that violate the SSP; i.e., Russian as well as French, although this latter language mostly adheres to the SSP; Hyman, 2008). In other words, the SSP and the SP describe a gradient based on the *Sonority Distance* (SDI henceforth) between phonemes, and especially between consonants within a C₁C₂ cluster (e.g., Selkirk, 1984; Wioland, 1991). They determine the phonological well-formedness and markedness of syllables in both onset and coda positions. Indeed, the least marked, and most well-formed, onset (i.e., phonotactically legal, *unmarked*) preferentially incorporates a maximal increase of the SP before the vowel (e.g., /tʁ/, SDI = +6.5), whereas the most marked, and most ill-formed, syllable (i.e., phonotactically illegal, *marked*) progressively describes a maximal decrease of the SP before the vowel (e.g., /ʁt/, SDI = -6.5). In contrast, an unmarked coda exhibits a minimal decrease in the SP after the vowel (e.g., /ʁt/), whereas a marked coda is characterised by a maximal decrease in the SP after the vowel (e.g., /tʁ/). In line with this principle,

¹ Throughout the manuscript, we sometimes use the term “acoustic-phonetic” because the clear-cut distinction between acoustic and phonetic remains controversial as well as its phonological nature (e.g., Boatman, 2004).

the *Syllable Contact Law* complements the SSP at the level of syllable boundary location and segmentation (e.g., Vennemann, 1988). Indeed, the universally optimal contact between consecutive syllables (i.e., well-formedness and markedness) reflects a reverse SP within syllable boundaries, with optimal contact between two consecutive syllables embedding a high-sonority coda immediately followed by a low-sonority onset (e.g., /paʁ.le/, *to talk*; the dot represents the syllable boundary). This makes the syllable boundary perceptually more salient. Both the SSP and the Syllable Contact Law are compatible with the *Maximal Onset Satisfaction Principle* that maximises the number of consonants in the syllable onset, provided that the phonological regularities of French mean that the cluster is phonotactically legal in the word-initial position (e.g., Spencer, 1996). (e.g., Spencer, 1996). For example, in a disyllabic word with a complex intervocalic cluster (e.g., C₁VC₂C₃V; ‘citron’, *lemon*), the syllabification is located between C₁V and C₂C₃V because ‘tr’ is considered as phonotactically legal in the word-initial position. However, in a disyllabic word with a cluster that French does not allow in the word-initial position (i.e., phonotactically illegal; e.g., ‘rt’ in C₁VC₂C₃V; ‘marteau’, *hammer*), the syllabification is located between C₁VC₂ and C₃V.

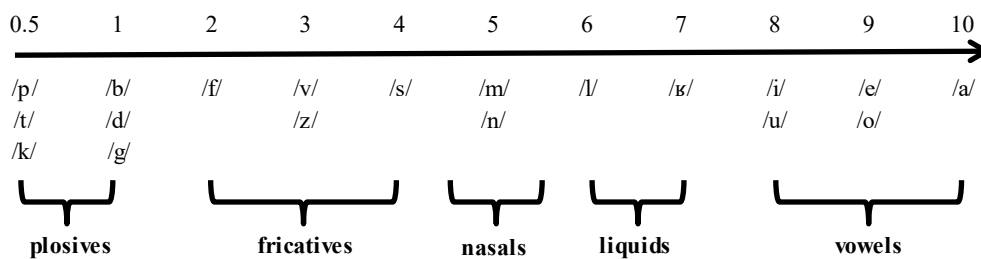


Figure 1. Sonority hierarchy inspired from Clements (1990) and Selkirk (1984).

Initial studies undertaken in order to test some of these linguistic principles have been conducted in preliterate and beginning readers, mostly at the level of speech production and reading aloud (e.g., Bastien-Toniazzo et al., 1999; Demuth & McCullough, 2009; Gnanadesikan, 2004; Hilaire-Debove & Kehoe, 2004; Sprenger-Charolles & Siegel, 1997). Taken together, their results highlighted that the children are prone to simplify complex structures such as CVC or CCV syllables to form simple structures such as CV syllables (e.g., ‘tru’ → ‘tu’ and ‘bar’ → ‘ba’) as a function of the consonant sonority that precedes or follows the vowel, with high-sonority consonants (e.g., /l/ or /ʁ/) being deleted more frequently than low-sonority consonants (e.g., /p/ or /k/) because of their low perceptual salience, and this regardless of the consonant position within the pseudowords (i.e., onset cluster [e.g., CCV] or coda cluster [e.g., CVC; CVCC]). All the results are consistent with language typologies that reveal the universal availability and well-formedness of CV structures (e.g., Clements, 2006).

However, a small number of studies have attempted to provide reliable evidence to determine whether – and how – consonant sonority and consonant position influence syllable segmentation and the simplification of complex syllable structures into simple ones in silent reading in French children (but see Fabre and Bedoin, 2003; Marouby-Terriou & Denhière, 2002). On the basis of the previous study of Fabre and Bedoin (2003) – the first authors to be interested in sonority in reading – Maïonchi-Pino et al. (2012a, 2012b, 2012c) designed four different SPs within syllable boundaries, which were used across different tasks (i.e., ‘sonorant coda–sonorant onset’ SP, ‘sonorant coda–obstruent onset’ SP, ‘obstruent coda–sonorant onset’ SP, and ‘obstruent coda–obstruent onset’ SP). For instance, in the work of Maïonchi-Pino et al. (2012b), the children were instructed to decide whether an audio-visually-presented disyllabic target pseudoword was identical to a test pseudoword or not. To determine how SPs influence (re-)syllabification strategies, they proposed an ‘identical’ condition (i.e., the target and test pseudowords were similar) and a ‘deletion’ condition in which either the coda (e.g., ‘TOLPUDE’ to be compared with ‘TOPUDE’) or the onset was deleted in the test pseudoword (e.g., ‘TOLPUDE’ to be compared with ‘TOLUDE’). First, the identical condition was processed faster, in particular in the case of optimal sonorant coda–obstruent onset SPs. Second, the children detected coda deletion faster than onset deletion provided that the optimal contact between syllables was

preserved (e.g., 'TOPUDE'). According to the authors, this suggests a sequential left-to-right processing that may take the form of either pure orthographic processing or phonological grapheme-to-phoneme correspondences processing (GPC henceforth). Taken together, it appears that the children progressively benefit from a sonority-modulated sensitivity that gradually enables them to use syllable segmentation. Furthermore, the clear-cut sonority-modulated syllable segmentation strategies seem to be quickly and automatically available, in particular with the optimal sonorant coda–obstruent onset SP. All their studies concluded that neither phonological properties (i.e., initial CV/CVC syllable frequency) nor orthographic properties (i.e., frequency of the initial bigram/trigram or the bigram that precedes, straddles or follows the syllable boundaries) accounted for the sonority-modulated syllable segmentation (for counter-arguments, see Doignon & Zagar, 2006; Doignon-Camus et al., 2013). However, some unanswered questions regarding the nature of syllable segmentation remain. Little has been discovered concerning the developmental course of the emergence of SSP sensitivity and (re-)syllabification strategies during reading acquisition in children, although both typically developing and even dyslexic children were sensitive to optimal SPs.

The aim of the present study was to shed light on an emerging debate about whether, when and how consonant sonority (sonorant vs obstruent) and consonant position within intervocalic clusters (coda vs onset) influence the developmental course of syllable segmentation strategies in French typically developing children. This issue is crucial since recent studies have disagreed as to whether, when and how the syllable becomes *the* reading unit in French. To answer this question, we propose reusing the audio-visual pseudoword recognition task that makes it possible to (a) examine all the possible SPs within syllable boundaries; (b) reflect the natural time course of speech and reading processes; (c) test the syllabification and re-syllabification strategies; (d) track developmental changes on the basis of response times [RTs], response accuracy and discrimination sensitivity (i.e., the *signal detection theory*, Macmillan & Creelman, 2005). However, an audio-visual presentation does not provide clear information about the nature of the codes activated in such a task. In an attempt to favour phonological codes and potentially exclude purely orthographically based codes, we used a visual version of the pseudoword recognition task. In light of the previous results reported by the Maïonchi-Pino et al. (2012a, 2012b, 2012c) studies, if segmentation strategies benefit from both the connections that are progressively established between implicit knowledge about phonological syllables (resulting from oral exposure) and explicit knowledge about written syllable-sized units (accumulated during reading acquisition; see the model proposed by Colé, Royer, Leuwers, & Casalis, 2004) and a sonority-based organisation that cues children where to locate the syllable boundaries, then we assume that performance will be better in response to the audio-visual presentation than the visual presentation. Indeed, an audio-visual presentation should permit the *powerful* encoding of the phonological and acoustic properties of the target pseudoword and a faithful decoding of the test pseudoword. It should also bring about better performance in detecting the match between target and test pseudowords with the sonorant coda–obstruent onset SP than any other SPs in the identical condition, as well as better performance in older than in younger children. Furthermore, because the use of syllable-sized units seems to be developmentally constrained in reading, a bidirectional syllable segmentation ((re-)syllabification strategies) that does depend on reading experience should be found. In younger children, coda deletion should be better detected because it preserves the original syllabification, whereas undifferentiated deletion effects were expected in the older children, even if onset deletion induces re-syllabification. Better performance should be observed for (re-)syllabification strategies as follows: in younger children, deleted coda and onset detection should stem from the perceptual salience of obstruent consonants (e.g., 'TO.LUDE' for 'TOL.PUDE' and 'DA.LORE' for 'DAT.LORE'). In older children, deleted coda and onset detection should depend solely on whether the test pseudowords exhibit optimal syllable contact (e.g., 'TO.PUDE' for 'TOL.PUDE', 'DA.TORE' for 'DAT.LORE' and 'BI.TADE' or 'BI.CADE' for 'BIC.TADE'). If the segmentation strategies primarily depend on pure orthographic codes, at least over pure phonological codes, the orthographic information such as bigram and trigram frequency should influence the segmentation strategies (i.e., [re-]syllabification) in both the visual and audio-visual presentations, regardless of the individual consonant sonorities.

Method

Participants

Three hundred typically developing French native-speaking children with normal or corrected-to-normal vision and hearing participated after their parents had returned a consent form. The children were of medium socio-economic status, were right-handed (+0.80 and +1 right-handedness scores measured with the Edinburgh Handedness Inventory; Oldfield, 1971) and had learned to read using a mixture of analytical GPC and global procedures. No child suffered from intellectual or psychological disorders or from any attention deficit hyperactivity disorder. This research received approval from the Regional School Management Office. Half of the children participated in the audio-visual presentation experiment ($N = 150$), and the other half in the visual presentation experiment ($N = 150$). On the basis of their reading experience calculated with a 20-min French standardised age-based word reading tests (TIMÉ 2, Écalle, 2003; TIMÉ 3, Écalle, 2006), the children were subdivided into five groups of 30 participants each for each experiment (i.e., first-year beginning readers, second-year beginning readers, third-year intermediate readers, fourth-year intermediate readers and fifth-year advanced readers). Their scores were not analysed. No child exhibited a reading level more than 12 months more or less than that expected for their chronological age ($M = 3.1 \text{ months} \pm 5.0$, $\text{min} = -7$, $\text{max} = 12$). Pairwise Student *t*-tests on chronological ages and reading level confirmed that each group differed from each other (all the $p_s < .0001$). The profiles of the children are reported in Table 1.

Material and design

The experimental stimuli consisted of 24 seven-letter disyllabic pseudowords with regular GPC (Table 2). The disyllabic pseudowords had an initial CVC syllable structure and a C_1C_2 intervocalic cluster without identical consonants (e.g., 'TAD.LITE'). All the syllable boundaries were systematically located within the C_1C_2 intervocalic clusters. We used Dell's (1995) list to select our C_1C_2 intervocalic clusters. Intervocalic C_1C_2 clusters were considered to be unattested in French if they were phonotactically illegal in the word-initial position (e.g., 'DL' is not permitted in the word-initial position² in French). Mean positional bigram frequencies were calculated from the French sub-lexical Surface database, which is itself derived from the Lexique 2 database (New, Pallier, Brysbaert, & Ferrand, 2004; Table 3) for the bigrams that precede, straddle and follow the syllable boundaries. Mean positional frequencies were estimated for the initial bigrams, trigrams and both CV and CVC syllables using the French sub-lexical Manulex-infra database (Peereman, Lété, & Sprenger-Charolles, 2007; Table 3), which provides print frequencies for French words encountered by first-grade to fifth-grade readers.

We made use of a 2×2 design (Coda Sonority \times Onset Sonority) for the SPs (sonorant and obstruent) within the C_1C_2 intervocalic clusters: sonorant coda–sonorant onset (e.g., 'TOR.LADE'), sonorant coda–obstruent onset (e.g., 'TOL.PUDE'), obstruent coda–sonorant onset (e.g., 'DAT.LORE'), and obstruent coda–obstruent onset (e.g., 'PUC.TODE').

Both the target and test pseudowords took the form of black uppercase letters printed in 'Arial' font on a white background. The pseudowords covered between approximately 2.10° (test pseudowords) and 2.94° of visual angle (target pseudowords; $\pm 0.42^\circ$ per letter). The auditory counterparts of the target pseudowords (audio-visual presentation) were spoken aloud by a speech and language therapist (female French native speaker). All the sounds were digitally recorded, sampled at a rate of 44 kHz, converted into Sound Designer II format with 16-bit resolution and bandpass-filtered (0 Hz to 5,000 Hz). We used Praat software (Boersma & Weenink, 2011) to inspect – and remove if required – the acoustic–phonetic artefacts within the C_1C_2 intervocalic cluster waveforms. To ensure adherences to French stress locations, we made sure that the stress was carried by the final syllable (e.g., /pyd/ in /tɔlpyd/). The mean duration was 197 ± 23 milliseconds for the C_1C_2 intervocalic clusters, whereas the mean duration of the target pseudowords was 631 ± 52 milliseconds and that of the test pseudowords was 570 ± 39 milliseconds.

² We accept that /pt/ and /kt/ clusters are attested, although marked, in oral French syllable-initial position. Also, 'PT' is an attested, marked written cluster. However, its initial bigram and biphone frequencies are 0 (Manulex-infra; Peereman et al., 2007).

In the case of the audio-visual presentation, a first pseudoword, labelled as the target pseudoword, was audio-visually presented and then compared with a visually presented test pseudoword, whereas for the visual presentation only the target pseudoword was displayed. Each target pseudoword (e.g., ‘TOLPUDE’) was related to three possible test pseudowords. One of these was identical to the target pseudoword (i.e., ‘yes’ response), whereas the other two differed from the target pseudoword (i.e., ‘no’ responses) after cluster reduction, that is to say, either in the coda deletion (i.e., ‘TOPUDE’) or in the onset deletion (i.e., ‘TOLUDE’) condition. Each target pseudoword was repeated twice in the identical condition and twice in the deletion condition (i.e., once for coda deletion and once for onset deletion). The yes and no responses were counterbalanced and pseudo-randomised across the lists to avoid consecutive presentations of the coda and onset deletions for one and the same pseudoword.

Table 1. Profiles of the children for the first-year and second-year beginning readers, third-year and fourth-year intermediate readers, and fifth-year advanced readers.

	Group	N (boys/girls)	Chronological age	Range	Reading level
Audio-visual presentation	1st-year beginning readers	30 (15/15)	81.4 (2.5)	6;5-7;2	86.7 (3.4)
	2nd-year beginning readers	30 (12/18)	91.6 (2.8)	7;3-8;0	94.2 (4.5)
	3rd-year intermediate readers	30 (16/14)	103.0 (3.9)	8;0-9;1	103.2 (3.9)
	4th-year intermediate readers	30 (15/15)	114.6 (5.1)	8;10-10;2	117.2 (6.5)
	5th-year advanced readers	30 (14/16)	129.9 (3.4)	10;4-11;4	136.9 (5.7)

	Group	N (boys/girls)	Chronological age	Range	Reading level
Visual presentation	1st-year beginning readers	30 (13/17)	84.5 (2.8)	6;7-7;3	87.1 (3.3)
	2nd-year beginning readers	30 (12/18)	90.4 (2.5)	7;2-8;1	93.7 (3.8)
	3rd-year intermediate readers	30 (17/13)	101.0 (2.9)	8;2-9;3	102.1 (3.2)
	4th-year intermediate readers	30 (17/13)	116.5 (3.8)	9;0-10;4	118.0 (4.8)
	5th-year advanced readers	30 (15/15)	129.5 (3.5)	10;2-11;6	134.1 (3.8)

Note. N, number of children (sex ratio in parentheses); chronological and reading level ages are in months; ranges are in years, months (standard deviations in parentheses); reading level as measured by TIMÉ 2 or TIMÉ 3 (Écalte, 2003, 2006).

Table 2. List of the stimuli as a function of the Coda Sonority × Onset Sonority experimental design.

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

Table 3. Mean positional frequencies for bigrams that precede, straddle and follow the syllable boundary with Lexique 2 database (New et al., 2004; upper panel) and mean initial bigram, trigram, CV and CVC syllable frequencies with Manulex-infra database (Peereman et al., 2007; lower panel) for the Coda Sonority × Onset Sonority experimental design.

	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)
	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)

Procedure

The children were individually tested in a single 20-minute session. We used PsyScope X freeware (Cohen, McWhinney, Flatt, & Provost, 1993) on a PowerBook G4 laptop running under Mac OS X in order to design, compile and run the script. The children sat in a quiet room at a distance of ± 57 cm from the screen and wore Altec Lansing AHS 502i headphones (20 Hz – 20 kHz range, 32 Ω impedance; audio-visual presentation only). The sounds were binaurally administered at 65 dB sound pressure level. The test pseudowords were always displayed in the left visual field, whereas the target pseudowords were always displayed in the right visual field. Each trial was conducted as follows: a 500-millisecond vertically centred fixation cross ('+') was displayed in the left visual field before being replaced by a 75-millisecond flash mask ('XXXXXXXX'). The target pseudoword (e.g., 'TOLPUDE') was then displayed in the left visual field for 2,500 milliseconds at the same time as its auditory counterpart, which was played once (i.e., /tɔlpyd/; audio-visual presentation only). Then, a 250-millisecond blank screen was displayed followed by a second 75-millisecond flash mask. A 500-millisecond vertically centered fixation cross appeared in the right visual field before being replaced by a 75-millisecond flash mask, after which the test pseudoword was visually presented (e.g., 'TOLPUDE', 'TOPUDE', or 'TOLUDE') until the child responded. Finally, the test pseudoword was replaced by a 75-millisecond flash mask. The inter-trial interval was 1,000 milliseconds. The target and test pseudowords were always displayed in opposite visual fields in order to prevent visual matching strategies. The children were first trained with a practice list of eight trials administered with corrective feedback. No feedback was given for the experimental trials. The children were instructed to indicate as quickly and accurately as possible whether the target and test pseudowords were identical. Because the participants were right-handed, they had to press the 'p' or 'a' response keys to answer 'yes' or 'no', respectively. The trials were randomised. RTs and response accuracy were automatically recorded. The experimenter did not intervene during any session.

Results

We ran mixed-design repeated-measures ANOVAs with subject ($F1$) and item ($F2$) as random variables on correct RTs and response accuracy (84.7% of the data). The mixed-design, repeated-measures ANOVAs were run with Group (first-year beginning readers, second-year beginning readers, third-year intermediate readers, fourth-year intermediate readers and fifth-year advanced readers) and

Experiment (visual presentation and audio-visual presentation) as between-subjects factor and Coda Sonority (sonorant and obstruent), Onset Sonority (sonorant and obstruent), Condition (identical and deletion) and Deletion (coda and onset) as within-subject factors. Correct RTs were trimmed (i.e., for each child, RTs more than two standard deviations above or below the participant's mean were replaced by the child's mean RT [2.6% of the data]).

Discrimination sensitivity and decision criterion analysis

We also used the d' to test the discrimination sensitivity thresholds and the β to assess the decision criterion between the two presentations (i.e., *signal detection theory*; $d' = 0 \pm 5\%$ means random responses embedded between 47.5% and 52.5%; e.g., Macmillan & Creelman, 2005). None of the participants had a $d' = 0 \pm 5\%$. The d' values ($M = 2.64 \pm 0.65$) were ranked from very low sensitivity with very difficult detection ($\min d' = 0.95$; in visual presentation) to high sensitivity with easy detection ($\max d' = 4.08$; in audio-visual presentation). The β values ($M = 0.86 \pm 0.70$) were ranked from a trend towards a high level of liberalism ($\min \beta = 0.14$) to a trend towards a high level of conservatism ($\max \beta = 5.38$). Pairwise Student t -tests of the d' and the β computed for each group showed that, whatever the group, the decision criterion did not differ between the audio-visual and visual presentations ($.08 < p_s < .1$), whereas the discrimination sensitivity threshold was significantly lower in the visual presentation than in the audio-visual presentation condition in first-year beginning readers ($M = 1.89 \pm 0.51$ vs $M = 2.57 \pm 0.41$), $t(58) = 5.79$, $p < .0001$; in second-year beginning readers ($M = 2.03 \pm 0.47$ vs $M = 2.69 \pm 0.47$), $t(58) = 5.33$, $p < .0001$; in third-year intermediate readers ($M = 2.35 \pm 0.53$ vs $M = 2.95 \pm 0.59$), $t(58) = 4.17$, $p < .0001$; in fourth-year intermediate readers ($M = 2.58 \pm 0.55$ vs $M = 3.14 \pm 0.53$), $t(58) = 3.98$, $p < .001$; and in fifth-year advanced readers ($M = 2.91 \pm 0.44$ vs $M = 3.32 \pm 0.40$), $t(58) = 3.80$, $p < .0004$.

General analysis

We carried out a $5 \times 2 \times 2 \times 2 \times 2$ mixed-design, repeated-measures ANOVA (Group, Experiment, Condition³, Coda Sonority, and Onset Sonority) on the RTs and response accuracy. This revealed that all the main effects were statistically significant ($p_s < .01$; results described in the analysis for the identical and deletion conditions). Briefly, the children responded more accurately – but slower – to the audio-visual presentation (1,830 milliseconds; 91.3%) than to the visual presentation (1,653 milliseconds; 86.3%), $F(1, 290) = 47.20$, $p < .0001$, $\eta^2_p = 0.14$, $F(1, 176) = 18.81$, $p < .005$, $\eta^2_p = 0.10$; $F(1, 290) = 98.35$, $p < .0001$, $\eta^2_p = 0.25$, $F(1, 176) = 9.11$, $p < .003$, $\eta^2_p = 0.05$. Also, main effect of Group was significant, $F(4, 290) = 47.65$, $p < .0001$, $\eta^2_p = 0.40$, $F(1, 704) = 21.90$, $p < .0001$, $\eta^2_p = 0.20$; $F(4, 290) = 30.72$, $p < .0001$, $\eta^2_p = 0.30$, $F(1, 704) = 6.30$, $p < .0001$, $\eta^2_p = 0.04$ (results described for the identical and deletion conditions). Beyond the significance of the other interactions, the Group \times Experiment \times Condition \times Coda Sonority \times Onset Sonority interaction was marginally significant, $F(4, 290) = 2.21$, $p < .07$, $\eta^2_p = 0.03$, $F(2) < 2$. Because one of our main hypotheses related to condition, we ran a condition-separated $5 \times 2 \times 2 \times 2$ mixed-design ANOVA for the Group \times Experiment \times Coda Sonority \times Onset Sonority interaction. Data are reported in Tables 4 and 5 (identical condition and deletion condition, respectively).

Analysis of the identical condition

We first compared the RTs and the response accuracy in the identical condition. This comparison revealed a main effect of Experiment, $F(1, 290) = 65.43$, $p < .0001$, $\eta^2_p = 0.18$, $F(1, 88) = 14.79$, $p < .0002$, $\eta^2_p = 0.14$; $F(1, 290) = 88.02$, $p < .0001$, $\eta^2_p = 0.23$, $F(1, 88) = 5.73$, $p < .02$, $\eta^2_p = 0.06$, with the children responding faster and more accurately in response to the audio-visual presentation (1,474 milliseconds; 94.0%) than to the visual presentation (1,760 milliseconds; 89.0%). The main effect of Group was also significant, $F(4, 290) = 17.77$, $p < .0001$, $\eta^2_p = 0.20$, $F(4, 352) = 27.90$, $p < .0001$, $\eta^2_p = 0.24$; $F(4, 290) = 34.76$, $p < .0001$, $\eta^2_p = 0.32$, $F(1, 352) = 4.53$, $p < .001$, $\eta^2_p = 0.05$. Fisher's

³ In order to compare the identical condition with the deletion condition in the visual and audio-visual presentations, we collapsed the response times in the deletion condition as a function of the coda and onset sonority, regardless of the nature of the deletion (i.e., coda or onset). In the specific analysis for the deletion condition, we re-introduced the distinction between coda deletion and onset deletion.

least significance difference (LSD) post hoc tests (Bonferroni's adjusted α -level for significance, $p < .005$) showed that the older the children were, the faster and the more accurate they were (first-year beginning readers, 1,879 milliseconds, 87.5%; second-year beginning readers, 1,654 milliseconds, 88.5%; third-year intermediate readers, 1,593 milliseconds, 91.8%; fourth-year intermediate readers, 1,519 milliseconds, 94.0%; and fifth-year advanced readers, 1,440 milliseconds, 95.6%). The main effects of Coda Sonority, $F(1, 290) = 63.13, p < .0001, \eta^2_p = 0.18, F(1, 88) = 15.52, p < .0002, \eta^2_p = 0.15; F(1, 290) = 25.45, p < .0001, \eta^2_p = 0.08, F(1, 88) = 3.61, p < .05, \eta^2_p = 0.03$, and Onset Sonority were significant $F(1, 290) = 72.70, p < .0001, \eta^2_p = 0.20, F(1, 88) = 8.42, p < .005, \eta^2_p = 0.09; F(1, 290) = 23.65, p < .0001, \eta^2_p = 0.08, F(1, 88) = 3.18, p < .05, \eta^2_p = 0.03$. The children responded to sonorant codas faster (1,554 milliseconds) and more accurately (92.5%) than to obstruent codas (1,680 milliseconds; 90.4%), while also responding to obstruent onsets faster (1,567 milliseconds) and more accurately (92.5%) than to sonorant onsets (1,668 milliseconds; 90.5%). The Coda Sonority \times Onset Sonority interaction was significant (Figures 2 and 3), $F(1, 290) = 23.87, p < .0001, \eta^2_p = 0.08, F(1, 88) = 4.02, p < .05, \eta^2_p = 0.04; F(1, 290) = 6.45, p < .01, \eta^2_p = 0.02, F(1, 88) < 2$. Fisher's LSD post-hoc tests (Bonferroni's adjusted α -level for significance, $p < .008$) showed that the children, irrespective of group and experiment, judged target and test pseudowords with sonorant coda–obstruent onset SPs (1,471 milliseconds) to be identical faster than they did the other SPs: sonorant coda–sonorant onset SPs (1,638 milliseconds); obstruent coda–sonorant onset SPs (1,698 milliseconds); and obstruent coda–obstruent onset SPs (1,663 milliseconds). Also, the children, irrespective of group and experiment, were more accurate when responding to identical target and test pseudowords with sonorant coda–obstruent onset SPs (94.1%) than with the other SPs: sonorant coda–sonorant onset SP (91.0%); obstruent coda–sonorant onset SP (89.9%); and obstruent coda–obstruent onset SP (90.9%).

Table 4. Mean response times (in milliseconds; upper line) and standard deviations (SD; in brackets) and mean response accuracy (in per cent; lower line) and the standard deviations (SD; in brackets) in the identical condition for the Experiment \times Coda Sonority \times Onset Sonority experimental design.

	Identical condition							
	Visual presentation				Audio-visual presentation			
	Sonorant onset		Obstruent onset		Sonorant onset		Obstruent onset	
	Sonorant coda	Obstruent coda	Sonorant coda	Obstruent coda	Sonorant coda	Obstruent coda	Sonorant coda	Obstruent coda
1st-year beginning readers	1683 (260)	1796 (227)	1513 (262)	1724 (276)	2098 (676)	2230 (659)	1870 (523)	2116 (678)
	82.2 (8.7)	81.4 (9.2)	87.5 (9.5)	82.0 (9.0)	91.4 (9.4)	90.3 (8.2)	94.2 (6.2)	90.8 (8.6)
2nd-year beginning readers	1582 (313)	1566 (274)	1399 (338)	1527 (311)	1817 (429)	1908 (379)	1629 (383)	1808 (325)
	82.8 (8.2)	82.2 (8.7)	88.6 (9.4)	85.3 (10.2)	91.9 (8.3)	92.0 (7.1)	94.5 (6.3)	90.8 (9.1)
3rd-year intermediate readers	1449 (294)	1438 (283)	1314 (316)	1460 (368)	1801 (353)	1827 (320)	1613 (266)	1845 (391)
	89.5 (8.7)	88.1 (8.4)	92.0 (7.7)	87.2 (9.7)	94.2 (7.0)	92.8 (6.1)	95.8 (5.2)	95.0 (6.8)
4th-year intermediate readers	1373 (346)	1418 (350)	1259 (289)	1463 (423)	1671 (376)	1744 (412)	1545 (345)	1680 (416)
	92.2 (8.7)	91.7 (7.9)	96.1 (6.5)	91.7 (9.0)	95.8 (6.5)	93.6 (7.8)	96.7 (4.7)	94.2 (7.6)
5th-year advanced readers	1383 (327)	1467 (247)	1217 (250)	1453 (256)	1523 (261)	1581 (275)	1348 (245)	1551 (357)
	91.7 (6.2)	93.9 (7.2)	97.2 (5.5)	94.7 (7.1)	96.1 (5.7)	93.6 (7.5)	98.1 (4.2)	97.2 (5.1)

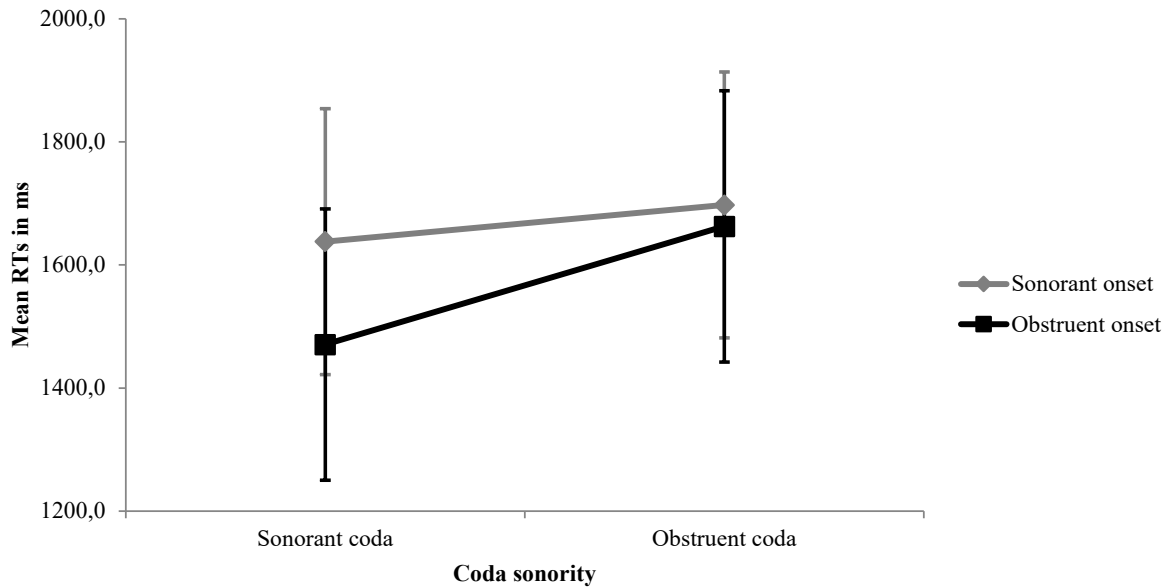


Figure 2. Mean response times (RTs) in milliseconds (ms) for the Coda Sonority × Onset Sonority in the ‘identical’ condition.

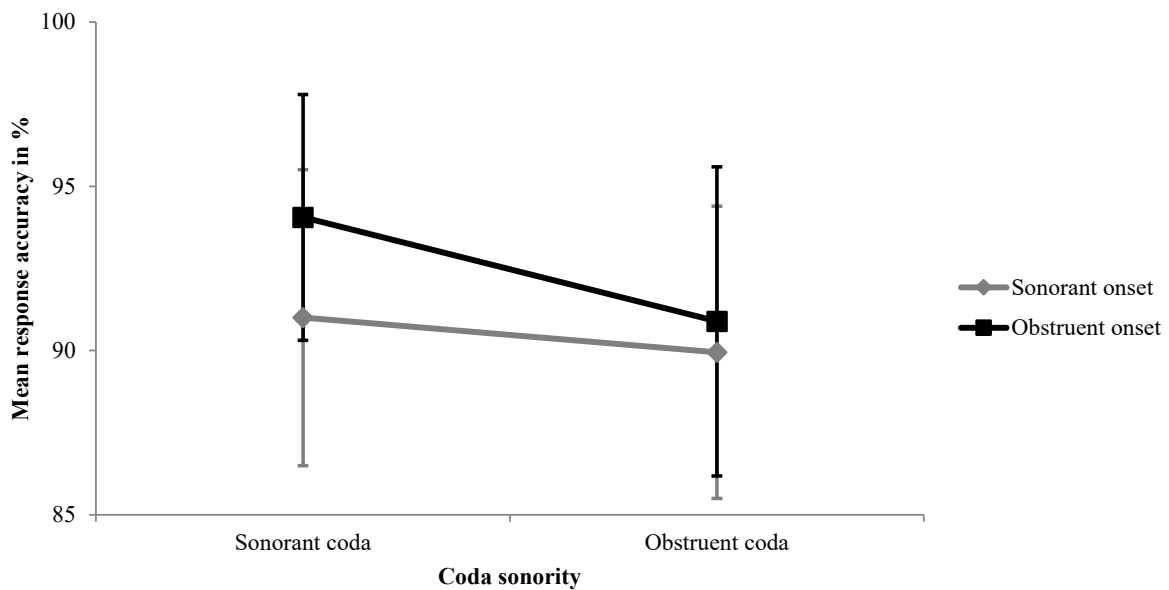


Figure 3. Mean response accuracy in percentage (%) for the Coda Sonority × Onset Sonority interaction in the ‘identical’ condition.

Analysis of the deletion condition

We next analysed the RTs and the response accuracy in the deletion condition. This analysis revealed a main effect of Experiment, $F1(1, 290) = 6.09, p < .01, \eta^2_p = 0.02, F2(1,80) = 69.85, p < .0001, \eta^2_p = 0.47; F1(1, 290) = 36.28, p < .0001, \eta^2_p = 0.11, F2(1, 80) = 6.24, p < .01, \eta^2_p = 0.03$, with the children responding faster when the target and test pseudowords mismatched in the visual experiment (1,832 milliseconds) than in the audio-visual experiment (1,907 milliseconds) and being more accurate when the target and test pseudowords mismatched in the audio-visual experiment (88.6%) than in the visual experiment (83.6%). The main effect of Group was also significant, $F1(4, 290) = 47.47, p < .0001, \eta^2_p = 0.40, F2(4, 320) = 6.99, p < .0001, \eta^2_p = 0.08; F1(4, 290) = 9.84, p < .0001, \eta^2_p = 0.12, F2(4, 320) = 4.43, p < .003, \eta^2_p = 0.05$. Fisher’s LSD post hoc tests (Bonferroni’s adjusted α -level for significance, $p < .005$) showed that the older the children were, the faster and more accurate they were (first-year

beginning readers, 2,254 milliseconds, 83.0%; second-year beginning readers, 1,896 milliseconds, 84.2%; third-year intermediate readers, 1,796 milliseconds, 85.7%; fourth-year intermediate readers, 1,749 milliseconds, 87.3%; and fifth-year advanced readers, 1,653 milliseconds, 90.4%). The main effect of deletion was significant, $F(1, 290) = 72.06, p < .0001, \eta^2_p = 0.20, F(2, 80) = 10.31, p < .002, \eta^2_p = 0.11; F(1, 290) = 15.37, p < .0001, \eta^2_p = 0.05, F(2, 80) = 3.78, p < .05, \eta^2_p = 0.04$. The children were faster and more accurate for coda deletion (1,820 milliseconds; 87.7%) than for onset deletion (1,919 milliseconds; 84.5%). The main effect of Coda Sonority was significant in RTs only, $F(1, 290) = 18.87, p < .0001, \eta^2_p = 0.06, F(2, 80) = 9.63, p < .003, \eta^2_p = 0.10$. The main effect of Onset Sonority was marginally significant in RTs, $F(1, 290) = 2.01, p < .1, \eta^2_p = 0.03, F(2, 80) < 2$. The children were faster to process sonorant codas (1,849 milliseconds) than obstruent codas (1,889 milliseconds), whereas they tended to process obstruent onsets (1,867 milliseconds) faster than sonorant onsets (1,872 milliseconds). Moreover, coda deletion (1,820 milliseconds) was detected faster than onset deletion (1,919 milliseconds).

The Group \times Deletion interaction was also significant (Figures 4 and 5), $F(4, 290) = 5.40, p < .0003, \eta^2_p = 0.07, F(2, 80) < 2; F(4, 290) = 3.30, p < .01, \eta^2_p = 0.04, F(2, 80) < 2$. Fisher's LSD post hoc tests (Bonferroni's adjusted α -level for significance, $p < .001$) indicated that RTs and response accuracy differed between coda deletion and onset deletion in first-year beginning readers (2,094 milliseconds vs 2,302 milliseconds; 87.2% vs 78.8%), in second-year beginning readers (1,918 milliseconds vs 2,077 milliseconds; 85.7% vs 82.2%), and in third-year intermediate readers (1,738 milliseconds vs 1,855 milliseconds; 87.4% vs 84.0%). There was no difference between the two types of deletion in the other groups.

Table 5. Mean response times (in milliseconds; upper line) and standard deviations (SD; in brackets) and mean response accuracy (in %; lower line) and the standard deviations (SD; in brackets) in the deletion condition for the Experiment × Coda Sonority × Onset Sonority × Deletion experimental design.

	Deletion condition															
	Visual presentation								Audio-visual presentation							
	Sonorant onset				Obstruent onset				Sonorant onset				Obstruent onset			
	Sonorant coda		Obstruent coda		Sonorant coda		Obstruent coda		Sonorant coda		Obstruent coda		Sonorant coda		Obstruent coda	
Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	Coda deletion	Onset deletion	
1st-year beginning readers	2258 (520)	2439 (538)	2099 (540)	2306 (575)	2409 (464)	2318 (592)	2307 (644)	2340 (595)	2188 (389)	2484 (465)	1828 (371)	2248 (432)	2092 (596)	1996 (370)	2268 (422)	2429 (451)
	81.7 (20)	75.0 (18)	88.3 (24)	76.1 (17)	85.6 (17)	81.1 (18)	83.9 (17)	72.2 (18)	87.2 (17)	81.7 (21)	93.9 (21)	78.9 (15)	88.9 (19)	84.4 (17)	88.3 (18)	80.6 (18)
2nd-year beginning readers	1691 (391)	1934 (462)	1677 (519)	1821 (417)	1701 (478)	1818 (454)	1783 (453)	1927 (448)	1931 (273)	2063 (364)	1798 (234)	2029 (246)	1967 (345)	1985 (291)	1976 (265)	2181 (263)
	82.2 (20)	78.3 (19)	86.7 (21)	80.6 (18)	83.9 (19)	82.2 (16)	81.1 (24)	77.8 (18)	87.2 (18)	82.8 (14)	91.7 (16)	81.7 (17)	85.6 (23)	89.4 (14)	87.2 (23)	85.0 (16)
3rd-year intermediate readers	1656 (267)	1788 (280)	1535 (245)	1803 (283)	1675 (266)	1723 (340)	1698 (268)	1835 (282)	1832 (258)	1885 (287)	1751 (287)	1958 (311)	1871 (280)	1712 (254)	1884 (272)	2087 (248)
	83.9 (18)	81.1 (18)	90.0 (15)	80.6 (16)	86.7 (24)	85.6 (14)	80.0 (19)	82.2 (16)	90.0 (15)	86.1 (16)	94.4 (15)	83.3 (12)	90.0 (23)	90.6 (11)	88.9 (20)	87.2 (13)
4th-year intermediate readers	1683 (227)	1642 (239)	1427 (266)	1655 (301)	1771 (296)	1604 (244)	1771 (269)	1943 (277)	1818 (266)	1918 (211)	1695 (234)	1787 (272)	1859 (295)	1755 (215)	1770 (207)	1831 (206)
	82.2 (14)	83.3 (13)	89.4 (13)	81.7 (15)	85.6 (15)	86.7 (16)	81.7 (18)	82.2 (17)	88.9 (13)	91.1 (12)	94.4 (11)	87.8 (13)	89.4 (15)	92.8 (12)	89.4 (13)	88.9 (14)
5th-year advanced readers	1618 (245)	1681 (227)	1502 (211)	1757 (249)	1806 (197)	1621 (288)	1620 (254)	1649 (233)	1766 (222)	1695 (269)	1466 (244)	1613 (259)	1685 (235)	1537 (221)	1666 (260)	1707 (254)
	85.6 (12)	86.1 (12)	93.9 (8)	86.7 (13)	90.0 (12)	91.7 (11)	83.3 (14)	86.7 (12)	89.4 (12)	90.0 (11)	95.6 (7)	91.1 (12)	91.1 (11)	95.0 (8)	92.2 (11)	92.8 (10)

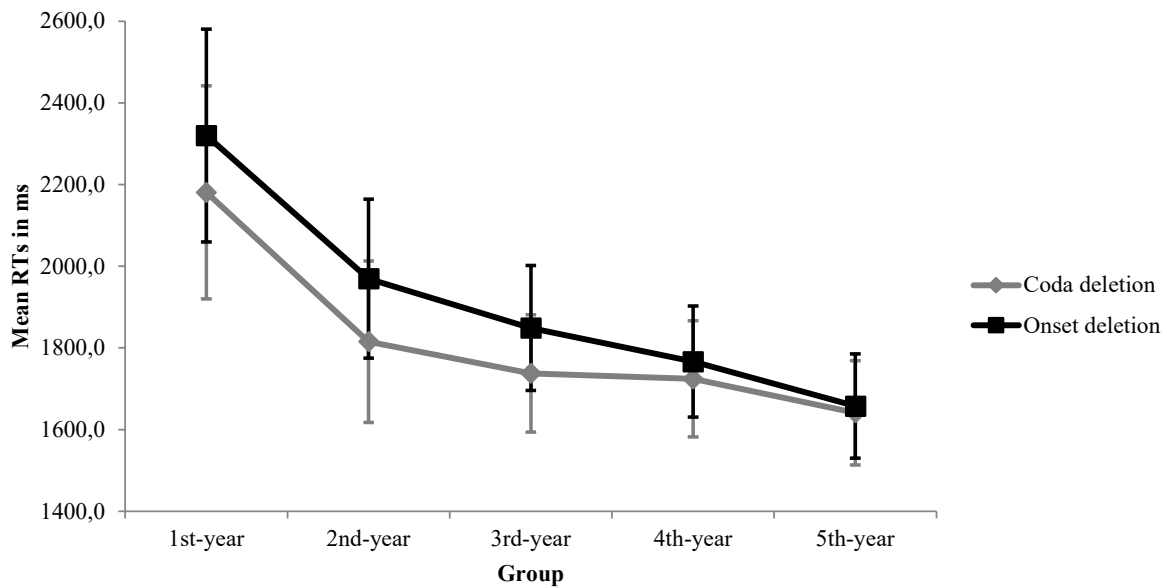


Figure 4. Mean response times (RTs) in milliseconds (ms) for the Group × Deletion interaction in the ‘deletion’ condition.

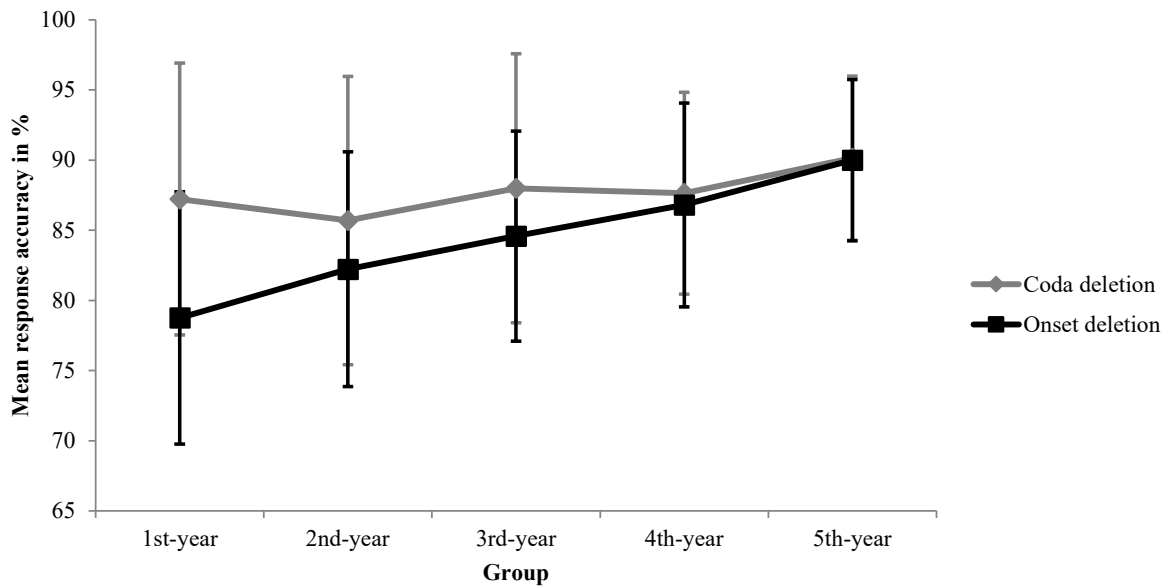


Figure 5. Mean response accuracy in percentage (%) for the Group × Deletion interaction in the ‘deletion’ condition.

There was also a significant Coda Sonority × Onset Sonority interaction, $F(1, 290) = 85.15, p < .0001, \eta^2_p = 0.23, F(1, 80) = 4.30, p < .04, \eta^2_p = 0.05; F(1, 290) = 26.19, p < .0001, \eta^2_p = 0.08, F(1, 80) = 3.60, p < .05, \eta^2_p = 0.03$. Fisher’s LSD post hoc tests (Bonferroni’s adjusted α -level for significance, $p < .008$) indicated that children, irrespective of group⁴, were faster and more accurate to detect that the target and test pseudowords mismatched when the target letter was deleted in the sonorant coda–obstruent onset SP (1,800 milliseconds; 87.3%) than in the obstruent coda–obstruent

⁴ The Group × Coda Sonority × Onset Sonority interaction was not significant. However, our group-by-group analyses for the Coda Sonority × Onset Sonority interaction confirmed our results for each group.

onset SP (1,934 milliseconds; 84.7%), the obstruent coda–sonorant onset SP (1,845 milliseconds; *ns*), and the sonorant coda–sonorant onset SP (1,899 milliseconds; 84.6%). Similarly, there were significant differences between all the other SPs, except for between the obstruent coda–obstruent onset SP and the sonorant coda–sonorant onset SP in the response times, whereas the obstruent coda–sonorant onset SP (87.7%) differed significantly from the obstruent coda–obstruent onset SP, and the ‘sonorant coda–sonorant onset SP in the response accuracy. There was no significant difference between the obstruent coda–sonorant onset SP and the sonorant coda–obstruent onset SP.

The Coda Sonority × Onset Sonority × Deletion interaction was marginally significant in the RTs but significant in the response accuracy, $F(1, 290) = 2.47, p < .09, \eta^2_p = 0.01, F(2 < 2; F(1, 290) = 3.86, p < .05, \eta^2_p = 0.01, F(2 < 2$. We analysed the Coda Sonority × Onset Sonority separately for both coda deletion and onset deletion in order to confirm our hypotheses. Fisher’s LSD post hoc tests (Bonferroni’s adjusted α -level for significance, $p < .002$) revealed that the children, irrespective of group, were faster and more accurate to detect that the target and test pseudowords mismatched when the deleted target letter was a sonorant coda in the sonorant coda–obstruent onset SPs (1,678 milliseconds, 91.7%; e.g., ‘TO.PUDE’ for ‘TOL.PUDE’) than in the case of any coda deletion in the other SPs: ‘sonorant coda–sonorant onset’ SP (1,844 milliseconds, 85.7%; e.g., ‘DA.RITE’ for ‘DAL.RITE’); ‘obstruent coda–sonorant onset’ SP (1,884 milliseconds, 87.6%; e.g., ‘DA.LORE’ for ‘DAT.LORE’); and obstruent coda–obstruent onset SP (1,874 milliseconds, 85.7%; e.g., ‘BI.TADE’ for ‘BIC.TADE’). The children, irrespective of group, were faster and more accurate to detect that the target and test pseudowords mismatched when the deleted target letter was a sonorant onset in the obstruent coda–sonorant onset SP (1,807 milliseconds, 87.8%; e.g., ‘DA.TORE’ for ‘DAT.LORE’) than in the case of any onset deletion in the other SPs: sonorant coda–sonorant onset SP (1,953 milliseconds, 83.6%; e.g., ‘DA.LITE’ for ‘DAL.RITE’); sonorant coda–obstruent onset SP (1,923 milliseconds, 82.8%; e.g., ‘TO.PUDE’ for ‘TOL.PUDE’); and obstruent coda–obstruent onset SP (1,993 milliseconds, 83.7%; e.g., ‘BI.CADE’ for ‘BIC.TADE’).

Additional analysis

In order to check how the statistical properties contribute to performance, we conducted a linear stepwise regression analysis with hierarchically forced entries of predictors in the response accuracy for both the identical and deletion conditions together (also collapsed across the audio-visual and visual tasks because the response patterns were similar; Table 6). To ensure that the statistical properties did not primarily influence the detection and segmentation patterns, we included both orthographic and phonological frequencies and an additional parameter: the phonotactic transitional probabilities (e.g., *Crouzet, 2000*).

Table 6. Linear stepwise regression analyses in the response accuracy for both the identical and deletion conditions and the audio-visual and visual tasks collapsed with hierarchically forced entries of predictors.

	Step	Predictor	R ²	R ² change	F change	p-level	β
Statistical properties	1	bigram frequency (that straddles)	.09	.05	3.79	.06	-.19
	2	initial bigram frequency	.11	.08	< 1	<i>ns</i>	.06
	3	initial trigram frequency	.11	.09	< 1	<i>ns</i>	.09
	4	initial CV syllable frequency	.13	.12	< 1	<i>ns</i>	.09
	5	initial CVC syllable frequency	.20	.15	1.15	<i>ns</i>	.12
	6	phonotactic transitional probabilities	.25	.19	2.22	.08	-.15

General discussion

We have reported the results of an audio-visual pseudoword recognition task and a visual pseudoword recognition task. Both tasks were designed to examine whether, when and how consonant sonority (sonorant vs obstruent) and consonant position within intervocalic clusters (coda vs onset) influence the developmental course of syllable segmentation strategies in French first-year beginning readers through fifth-year advanced readers.

As predicted, the children were more efficient in response to the audio-visual presentation than the visual presentation. The difference in the discrimination sensitivity thresholds between the two tasks means that the dual presentation of the target pseudowords improved the judgement of the test pseudowords as identical or different, regardless of the participant's reading experience. Additionally, the decision criteria did not differ, with the children being confident in their responses across the tasks. We therefore observed a 'qualitative-quantitative' asymmetry. The fact that the participants performed better in response to the audio-visual presentation than to the visual presentation in the identical condition and the deletion condition was confirmed by the response accuracy analysis, whereas the RT analysis showed that, for both conditions, performance was worse in response to the audio-visual presentation than to the visual presentation. This 'speed-accuracy' trade-off reinforces our hypothesis that the audio-visual presentation permits a powerful encoding of the phonological and acoustic properties of the target pseudoword and a faithful decoding of the test pseudoword. Indeed, phonological and acoustic-phonetic properties might require more pre-processing, that is, a longer encoding phase for the target pseudowords, and more post-processing, that is, a longer decoding phase for the test pseudowords. This simultaneously slows down and improves the analysis. This is true, in particular, in the deletion condition, which is ambiguous and involves (re-)syllabification strategies. The visual presentation seems to be sufficient for the processing of unambiguous stimuli but exhibits some limitations. It fits well with the hypothesis that efficient silent reading in children is based on the progressive development of functional links between spoken and written representations (e.g., Ziegler & Goswami, 2005).

What remains uncertain is what the prelexical and segmental unit is. To investigate our hypothesis, we monitored certain developmental changes in RTs and response accuracy. This confirmed that the use of syllable-sized units and syllable segmentation strategies depends on some developmentally based constraints. On the one hand, the older the children, the faster and more accurate they were in both the identical and deletion conditions. On the other, although the participants were systematically more successful in the identical condition than in the deletion condition, the RTs and response accuracy when deciding whether target and test pseudowords (mis)matched depended on reading experience and the position of the deleted consonant. Indeed, a difference between coda and onset deletions was found in first-year beginning readers, second-year beginning readers and third-year intermediate readers: coda deletion was detected faster and more accurately than onset deletion. There was no difference in fourth-year intermediate and fifth-year advanced readers.

The fact that children's performance changes over time corroborates previous studies and does not challenge the idea that syllable segmentation is used. As we have suggested, these response patterns seem to be compatible with the idea of a bidirectional syllable segmentation ([re-]syllabification strategies) that is underpinned by reading experience and is typically found in developmental studies of silent reading (e.g., Maionchi-Pino et al., 2010b, 2012c). More specifically, these response patterns could result from the connections that are progressively established between implicit knowledge about phonological syllables (due to oral exposure) and explicit knowledge about written syllable-sized units (during reading acquisition; e.g., Colé et al., 2004). These patterns are involved in the development of the phonological awareness that is essential in order to learn how to read. The development of phonological awareness is a universal prerequisite that naturally emerges through implicit oral language experiences before developing more fully in response to the explicit teaching of reading. Phonological awareness refers to the ability to perceive, identify, analyse and manipulate phonological sequences and determines how sounds can be segmented into smaller units (e.g., syllables > phonemes) or blended into larger ones (e.g., phonemes > syllables; e.g., Castles & Coltheart, 2004). Furthermore, the earlier children understand that words are made up of smaller sound units, the better they learn the GPC, while the GPC strengthens the phonological awareness required to sequence, segment or blend sound units (e.g., Share, 1995).

On the basis of this developmental framework, younger children seem to be able to use sequential left-to-right processing that is likely to involve phonological GPC processing instead of purely orthographic processing, in particular in the case of preserved syllabification (i.e., coda deletion). As phonological awareness develops, this sequential left-to-right processing disappears to be replaced by generalised syllable segmentation, thus explaining the undifferentiated deletion effects in older children. This interpretation also fits with Ehri's (2005) proposal. Learning to read follows a

small-to-large developmental sequence that progresses from grapho-phonemic processing, and away from reliance on GPC, to grapho-syllabic processing. GPC therefore progressively becomes consolidated and unitised into larger units, thus reducing the number of isolated phonemic units (in French, 26 phonemes) to a small number of syllabic chunks like in French (e.g., CV, CCV, CVC and VC).

Moreover, coda deletion suggests that French children reliably access syllable-sized units in reading at an early age. More importantly, their fragile sensitivity to syllable structures, which induces the simplification of complex syllable structures into simple ones, grows stronger with reading experience (e.g., Sprenger-Charolles & Siegel, 1997; Maionchi-Pino et al., 2012a, 2012b). This development is compatible with the preference for the simple, optimal CV syllables that respect the SDI (i.e., low-sonority initial consonant + vowel) and the prevalence of CV syllable structures over CVC structures in French (e.g., 56% vs 19%; Dauer, 1983).

In our study, the children exhibited sonority-based pseudoword recognition and segmentation. A sonority-based organisation cued children to recognise and locate the syllable boundaries and segment pseudowords. As we expected, the children detected the match between target and test pseudowords with the sonorant coda–obstruent onset SP in the identical condition. The fact that they preferred the sonorant coda–obstruent onset SP is crucial because it indicates that, at an early age, children are sensitive to the intrinsic properties of phonemes, their organisation (i.e., the SSP; Clements, 2006) and the clear-cut gap within the syllable boundaries when processing written stimuli (i.e., the Syllable Contact Law; e.g., Vennemann, 1988). The children exhibited an acoustic–phonetic position-dependent sensitivity to coda and onset in both the identical and deletion conditions. Indeed, their sensitivity to sonority extends to individual consonants and complements both the SSP and the Syllable Contact Law. The children detected the match between target and test pseudowords with sonorant consonants with optimal coda positions better than obstruent codas, whereas they detected the match between target and test pseudowords with obstruent consonants with optimal onset position better than sonorant onsets. In the identical condition, the children benefited from the appropriate acoustic–phonetic position-dependent expectations within the syllable boundaries, which enabled them to perform a straightforward and uncontroversial analysis (i.e., forward processing for preserved syllabification). This was also true when the children had to detect the mismatch between target and test pseudowords. In the deletion condition, the increase in the RTs while the response accuracy was constant suggests that there is a further process underlying the fine-grained reanalysis of the acoustic–phonetic position-dependent expectations within the syllable boundaries, which leads to the use of an appropriate (re-)syllabification (i.e., backward processing for re-syllabification). However, the results that we found in the deletion condition did not fully support our hypothesis, namely that sonorant coda deletion may stem from a low perceptual salience compared with that of obstruent consonants. Surprisingly, the response patterns did not bear out the argument according to which the closer the consonant sonority is to the vowel, the more often the deletion or omission arises (e.g., Gnanadesikan, 2004). There was therefore no significant preference for deletion at the level of the perceptual salience of obstruent consonants in younger children (e.g., ‘TO.LUDE’ for ‘TOL.PUDE’ and ‘DA.LORE’ for ‘DAT.LORE’). Instead, the children detected the coda or onset deletion only when the SSP and the Syllable Contact Law were maximised (or optimised). The children detected sonorant coda deletion within the sonorant coda–obstruent onset SP (e.g., ‘TO.PUDE’ for ‘TOL.PUDE’) and sonorant onset deletion within the obstruent coda–sonorant onset SP (e.g., ‘DA.TORE’ for ‘DAT.LORE’) better than any other deletions within the other SPs. This was true in both the audio-visual and visual presentations, thus emphasising that syllablesized segmentation and the retrieval of sonority-based properties did not require the use of oral material. These response patterns indicate that phonological awareness influences the way syllable segmentation is used for written stimuli, whereas sonority-based organisation might maximise cohesiveness in – and between – syllables and might form part of general phonological knowledge that is consistent with language-specific constraints (for more details, see the optimality theory; Prince & Smolensky, 2004).

Unlike in the case of our alternative hypothesis, we discarded the idea that statistical properties can account for our results, in particular regarding the bigram trough hypothesis⁵, as all the SPs had a bigram trough (M range = 0–954; $M = 273$). We also observed that the sonorant coda–sonorant onset SPs that embed high-frequency initial trigrams (from 0 to 218; $M = 70$), high-frequency syllables (from 0 to 195; $M = 43$) and high-frequency bigrams that precede syllable boundaries (from 3,055 to 7,811; $M = 4,728$) did not improve or hinder the detection of the match or the mismatch between the target and test pseudowords. Similarly, we found that the obstruent coda–obstruent onset SPs that embed low-frequency initial trigrams (from 0 to 84; $M = 17$), low-frequency syllables (from 0 to 2; $M = 1$) and low-frequency bigrams that precede syllable boundaries (from 327 to 2,262; $M = 1,040$) did not improve or hinder the detection of the match or the mismatch between the target and test pseudowords. As can be seen in Table 6, neither the orthographic nor phonological frequencies primarily explain our results and provide no clear evidence that frequency impacted the response patterns and or had either inhibitory or facilitatory effects (for more details, see Chetail & Mathey, 2009b; Maïonchi-Pino et al., 2010b). Because the statistically based results were not clear-cut, we can dismiss the idea that, in our experiments, the children only and primarily benefited from statistical properties rather than sonority-based properties.

Conclusion

Taken together, our results confirm previous studies relating to the contribution of consonant sonority and consonant position within intervocalic clusters to syllable segmentation strategies in French children (e.g., Maïonchi-Pino et al., 2012b, 2012c). Children experience early and long-lasting sensitivity to sonority-based linguistic principles such as the SSP and the Syllable Contact Law. What is new in our findings is that we observed that the children were able to detect the match or the mismatch between target and test pseudowords as long as the sonority organisation within the syllable boundaries was optimal (i.e., sonorant coda–obstruent onset SP in the identical condition and a high-sonority vowel followed by a low-sonority onset in the deletion condition). More importantly, we highlighted the fact that both were used as acoustic–phonetic cues in visual word recognition and syllable segmentation, in response to both an audio-visual presentation and a visual presentation, although the response patterns were more reliable with a dual audio-visual presentation. This is an important observation because several recent studies have shown that audio-visual training has a strong impact on the development of GPC abilities (e.g., Écalle, Kleinsz, & Magnan, 2013). Our results also described a progression in the use of the syllable. Even though we observed reliable sonority-modulated syllable segmentation, it gradually evolved to become systematic in around the third year (i.e., intermediate readers), thus confirming the importance of the syllable as a reading unit. It is interesting to note that these findings could be extended to other languages, for instance Romance languages, with similar syllable segmentation in reading (e.g., Spanish and Italian). Although counterintuitive in light of previous studies, we showed that this preference was more universal than reliance on statistical properties in French (Doignon & Zagar, 2006). Accordingly, we adhere to the theoretical view that phonological regularities encompass language-specific rules that govern how – and how frequently – phonemes occur and co-occur at specific positions in French (i.e., phonotactic constraints and statistical properties, respectively). However, we emphasise that phonological regularities and syllable segmentation strategies primarily respect the SSP, the Syllable Contact Law and the Maximal Onset Satisfaction Principle.

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⁵Research into statistical orthographic properties addresses the issue of the bigram trough hypothesis. The bigram trough hypothesis assumes that bigrams that straddle syllable boundaries are of a lower frequency than bigrams that surround syllable boundaries, which is a powerful statistical cue to underpin – even improve – word parsing and syllable effects, in particular in French children (e.g., Doignon-Camus et al., 2013; Doignon & Zagar, 2006).

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