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Early Speech Segmentation in French-learning Infants: Monosyllabic Words versus Embedded Syllables

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Abstract

Lexical acquisition relies on many mechanisms, one of which corresponds to segmentation abilities, that is, the ability to extract word forms from fluent speech. This ability is important since words are rarely produced in isolation even when talking to infants. The present study explored whether young French-learning infants segment from fluent speech the rhythmic unit of their native language, the syllable. Using the Headturn Preference Procedure and the passage word order, we explored whether these infants can segment monosyllabic words (at 6 and 8 months), syllables embedded in bisyllabic words (at 6 months) and bisyllabic words (at 6 months). Our results bring direct evidence in support of the early rhythmic segmentation hypothesis, by establishing syllabic segmentation both for monosyllabic words and embedded syllables at 6 months, while failing to find segmentation of bisyllabic words at the same age. They also indirectly extend to French previously reported effects of coarticulation, acoustic variation and infant-directed speech on segmentation found in English. Therefore, our study contributes to a better understanding of the similarities and differences in early segmentation across languages, and thus to a better understanding of the mechanisms underlying segmentation.

Keywords

Early speech segmentation, syllabic unit, French-learning infants, 6- and 8-month-olds

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1 Introduction

Infants are born with impressive perceptual skills to rapidly acquire the properties of their native language, such as its phonology, lexicon and syntax. The present study explores one of the mechanisms involved in learning a lexicon, namely the ability to segment, that is, to extract, the sound patterns of words from fluent speech. Word form segmentation constitutes a crucial step in lexical acquisition, because words mostly occur within sentences and only rarely in isolation (Aslin, 1993; Brent & Siskind, 2001), and a few findings established links between early segmentation and later language competence (Graf Estes et al., 2007; Kooijman, Junge, Johnson, Hagoort, & Cutler, 2013; Newman et al., 2006). Many studies have explored the emergence of word form segmentation, using either behavioural methods (e.g., Headturn Preference Procedure, or HPP) or electrophysiological methods (e.g., Evoked-Response Potentials, or ERPs), and have established that this ability emerges around eight months of age in infants learning English (Jusczyk & Aslin, 1995; Saffran, Aslin, & Newport, 1996), Parisian French (Goyet, Nishibayashi, & Nazzi, 2013; Mersad & Nazzi, 2012; Nazzi, Mersad, Sundara, Iakimova, & Polka, 2014), Canadian French (Polka & Sundara, 2012; Shi, Marquis, & Gauthier, 2006), Dutch (Houston, Jusczyk, Kuijpers, Coolen, & Cutler, 2000; Kooijman, Hagoort, & Cutler, 2005; Kooijman et al., 2013) and German (Höhle & Weissenborn, 2003). The goal of the present study was to investigate the early use, in French-learning infants, of the rhythmic unit of French, namely, the syllable, for segmenting monosyllabic words and syllables that are embedded in bisyllabic words.

Previous research has established that during the first year of life, infants use many subtle linguistic cues present in the signal to identify boundaries between words. These cues include transitional probabilities (TPs, referring to distributional regularities in the order of syllables in the speech signal: Johnson & Jusczyk, 2001; Mersad & Nazzi, 2012; Saffran, Johnson, Aslin, & Newport, 1999), the rhythmic unit of the native language (Curtin, Mintz, & Christiansen, 2005; Goyet, de Schonen, & Nazzi, 2010; Goyet et al., 2013; Jusczyk, Houston, & Newsome, 1999; Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006), prosodic boundaries (Gout, Christophe, & Morgan, 2004; Seidl & Johnson, 2006), coarticulatory cues (Johnson & Jusczyk, 2001), allophonic information (Jusczyk, Hohne, & Bauman, 1999), phonotactic information (Gonzalez Gomez & Nazzi, 2013; Mattys, Jusczyk, Luce, & Morgan, 1999; Mattys & Jusczyk, 2001), known words (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005; Mersad & Nazzi, 2012) and pitch accent (Nazzi, Dilley, Jusczyk, Shattuck-Hunagel, & Jusczyk, 2005). The hypothesis regarding the use of the rhythmic unit for segmentation, on which the present study focuses, is linked to "prosodic or phonological bootstrapping" theories (Morgan & Demuth, 1996), which claim that the speech signal contains many acoustic/prosodic cues that facilitate infants' learning of the properties of their native language, such as its basic rhythm (Nazzi, Bertoncini, & Mehler, 1998), its lexicon and some properties of that lexicon (Gleitman & Wanner, 1982; Jusczyk, Cutler, & Redanz, 1993) or its syntactic structure (Hirsh-Pasek et al., 1987). Accordingly, the early rhythmic segmentation hypothesis states that young infants use the rhythmic unit of their native language to segment the continuous speech stream (Nazzi et al., 2006). Given that languages have different rhythmic units (the trochaic or strong–weak stress unit in stress-based languages such as English, Dutch and German; Pike, 1945; the syllable in syllable-based languages such as French, Spanish, Catalan and Italian; Abercrombie, 1967), this hypothesis predicts that there should be cross-linguistic differences in the way segmentation abilities emerge during development.

Several studies investigated the early use of the trochaic unit (a sequence of syllables in which the first syllable is stressed) for segmentation in infants learning stress-based languages. In particular, Jusczyk, Houston, et al. (1999) conducted a series of 15 HPP experiments to explore the segmentation of bisyllabic words by English-learning infants. Depending on the experiments, infants were tested in two different ways: either by familiarizing them with two lists of repeated trochaic (strong–weak) or iambic (weak–strong) bisyllabic words and testing them with two passages containing the target words versus two passages containing novel words (word-passage order); or by familiarizing infants with two passages each containing a target word and testing them on lists of repetitions of the two target words versus lists of repetitions of two novel words (passage-word order). At 7.5 months, in both orders, English-learning infants segment and recognize trochaic words while not recognizing as targets the sole stressed syllables of the trochaic words. This suggests that these infants do not extract the initial stressed syllables of trochaic words independently. In contrast, English-learning infants fail to segment iambic words at 7.5 months. At that age, when familiarized with passages containing iambic words (e.g., guiTAR), they segment and recognize their sole stressed syllables (e.g., TAR), and when that syllable is consistently followed by the same weak syllable (e.g., is), they extract a trochaic sequence consisting of the final stressed syllable of the iambic word and the following weak syllable (e.g., TARis). In contrast, at 10.5 months, English-learning infants segment iambic words and stop segmenting the stressed syllables of these iambic words individually or in combination with a consistently following weak syllable. Taken together, these findings suggest that at the younger age (7.5 months), infants extract trochaic units whether or not they correspond to actual words, as long as the syllables in the trochaic units consistently co-occur in the signal. At the later age (10.5 months), they appear able to combine distributional (and probably coarticulation) information to segment word forms that do not conform to the rhythmic unit of English. Convergent findings were obtained for Dutch-learning infants at 9 months using HPP (Houston et al., 2000) and at 7 and 10 months using ERPs (Kooijman et al., 2005, 2013). The results on English- and Dutch-learning infants are thus compatible with the idea that the trochaic unit is used for early word form segmentation by infants learning stress-based languages, suggesting specialization to the native language in segmenting the speech stream during the first half of the first year of life.

What about early segmentation in syllable-based languages such as French, and the early use of the syllabic unit for segmentation in infants learning such languages? Two strategies have been employed to address this question, looking either at the segmentation of monosyllabic words or comparing the segmentation of bisyllabic words versus syllables embedded in bisyllabic words. Regarding the segmentation of monosyllabic words in French, Gout (2001), using HPP and the word-passage order, found that French-learning 7.5-month-olds could segment monosyllabic words, but could not replicate this finding in 10.5-month-old infants. These mixed findings require further exploration of this issue, in particular in light of recent evidence of monosyllabic word segmentation in Spanish-learning monolinguals, Catalan-learning monolinguals and Spanish-Catalan bilinguals at both 6 and 8 months of age (Bosch, Figueras, Teixidó, & Ramon-Casas, 2013), using HPP but the passage-word order. Experiment 1 of the present study will explore whether such early effects can also be found in French in the passage-word order (see below for further discussion of the importance of order effects).

While the above studies provide some evidence of early segmentation of monosyllabic words in syllable-based languages, it has been argued that such evidence is ambiguous when it comes to the issue of the syllable as a basis of segmentation because the syllabic and lexical levels are confounded in monosyllabic words (and because stressed syllables can also constitute trochaic feet in English, which can be segmented as early as 7.5 months; Jusczyk & Aslin, 1995). Nazzi et al. (2006) pointed out that stronger evidence of syllabic segmentation would be provided by data showing that infants segment individual syllables embedded in multisyllabic words before (in developmental time or in the order of processing) they segment whole bisyllabic words. In this context, what do we know, firstly, regarding whole word bisyllabic segmentation in French? In a first study, using HPP and the word-passage order, Nazzi et al. (2006) found an emergence of bisyllabic word segmentation between 12 and 16 months of age, potentially revealing a delay in the segmentation of words larger than the syllable in French-learning infants. However, more recent studies found earlier evidence of bisyllabic word segmentation, by 12 months using ERPs (Goyet et al., 2010), by 8 months using HPP and an artificial language paradigm (Mersad & Nazzi, 2012) and by 8 months using HPP in a population of infants learning Canadian French (Polka & Sundara, 2012). This later finding led to a further re-evaluation of bisyllabic word segmentation in (European) French-learning infants using HPP and natural language stimuli, which revealed that bisyllabic word segmentation can be found at 8 months in the passage-word order, but not before 16 months in the word-passage order, even when using the same stimuli (Nazzi et al., 2014). The authors proposed that this order effect in French-learning infants might be a result of the use of syllabic segmentation: if infants go through an initial process of segmenting syllables independently, they will need to use distributional information in order to form bisyllabic units. In the passage-word order, this information is provided to infants during the familiarization phase, and might thus be readily available at the test phase; on the contrary, in the word-passage order, this information gradually becomes available during the test phase, which might render the observation of a segmentation effect more difficult. Note that while such order effects should not be found for monosyllabic words cross-linguistically, nor for trochaic words in stress-based languages (since the segmentation of both types of words does not require distributional information), they might be found for early segmentation of iambic words in stress-based languages, a prediction that will have to be tested in future studies. In summary, the studies on French using bisyllabic words show that these words can be segmented as early as 8 months of age, in conditions in which infants have access to distributional information supporting the co-occurrence of these two syllables.

In this context, support for the early rhythmic segmentation hypothesis in syllable-based French would require that French-learning infants segment syllabic units by or before 8 months, and/or that in segmenting bisyllabic words, they go through an initial processing stage of segmenting individual syllables. In HPP experiments using the word-passage order, in which infants were familiarized with individual syllables and then tested on passages containing or not these syllables embedded in target bisyllabic words, evidence of syllabic segmentation had only been found at 12 months of age (Nazzi et al., 2006). However, more recent evidence using the passage-word order found such evidence as early as 8 months of age (Goyet et al., 2013). In that study, infants were familiarized with passages containing either two target bisyllabic words (each repeated four times) or eight target bisyllabic words (each presented once), and within each passage, all target words shared a target syllable (thus repeated eight times in both conditions). Moreover, syllables preceding and following the target words were all different. These manipulations were made so that in the two target word conditions, TPs between syllables around the target syllables remained informative of the fact that the target syllables were part of bisyllabic words, but about half less than in "classic" studies in which each passage only contained one repeated bisyllabic word. However, in the eight target word condition, TPs were uninformative of the fact that the target syllables were part of bisyllabic words, so that infants should process them as syllabic units. When tested on their recognition of the target syllables, infants succeeded in the eight target word condition but not in the two target word condition. Therefore, when distributional information (TPs) is neutralized, 8-month-old infants appear to be segmenting separately syllables embedded in bisyllabic words. Moreover, in the two target word condition, 8-month-old infants were also tested on their recognition of the target bisyllabic words, and failed to do so. This is important because it establishes that in the eight target word condition in which infants segmented the individual target syllable, they could not have segmented the eight target words first and then accessed the common syllable, since they could not even segment the bisyllabic words in the two target word condition. Therefore, Goyet et al. (2013) establishes that French-learning 8-month-olds segment individual syllables in a first segmentation step. It further suggests that in order to form bisyllabic units, they need the presence of consistent distributional information to attach the consecutive syllables in the speech stream, as was the case in Nazzi et al. (2014) in which bisyllabic word segmentation was found, but was not the case in Goyet et al. (2013) in which it was not found. Experiments 2 and 3 of the present study will use the eight target word condition of Goyet et al. (2013) to probe syllabic segmentation in younger, 6-month-old infants.

To summarize the goal of the present study, Experiment 1 was conducted, firstly, to assess French-learning 8-month-olds' abilities to segment monosyllabic words in the passage-word order, in order to extend the finding of Gout (2001) using the word-passage order. Secondly, it sought to determine whether these abilities can be found in infants as young as in Bosch et al. (2013), that is, at 6 months. Experiments 2 and 3 then explored whether French-learning 6-month-olds can segment syllables embedded in bisyllabic words in order to confirm the rhythmic-based segmentation hypothesis (Nazzi et al., 2006). Lastly, in Experiment 4, we tested the segmentation of whole bisyllabic words, to investigate the relative order of emergence of segmentation of syllabic units versus segmentation of bisyllabic words as found at 8 months in Nazzi et al. (2014). In all experiments, we used HPP and the passage-word order, with 30 (Experiments 1 and 2) or 45 s (Experiments 3 & 4) of familiarization to each passage. We chose to use 30 s familiarization times in our first two experiments because this is the duration under which the segmentation of bisyllabic words (Nazzi et al., 2014) and of syllables embedded in bisyllabic words (Goyet et al., 2013) was found for French-learning 8-month-olds. In Experiment 1, infants were familiarized with two passages, each containing eight repetitions of a monosyllabic word, and then tested on whether they had segmented those monosyllabic words by being presented with the two target monosyllabic words versus two control monosyllabic words.

2 Experiment 1

2.1 Method

2.1.1 Participants. Forty healthy full-term infants were included, 20 (12 females and 8 males) 8-month-olds (mean age: 8 months and 10 days; range: 8 months and 1 day to 8 months and 28 days) and 20 (9 females and 11 males) 6-month-olds (mean age: 6 months and 10 days; range: 6 months to 6 months and 27 days). Nine additional infants were tested but not included due to fussiness (5) or crying (4). All the infants were from monolingual French-speaking families. All parents gave informed consent before participation and completed an information sheet.

2.1.2 Stimuli. Four monosyllabic CV words (/di/, /po/, /te/, /gu/) were selected (see Table 1). As in previous research on this topic, these target words were nouns with relatively low frequencies, as given in the adult database LEXIQUE 2 (New, Pallier, Brysbaert, & Ferrand, 2004, given per 1 million occurrences, and calculated over a base of 31 million occurrences): /di/ = 4.86 (*dit* [a said]), /po/ = 32.3 (*pot* [pot]), /te/ = 44.19 (*thé* [tea]), /gu/ = 124.8 (*goût* [taste]). Moreover, they were not listed in the French MCDI (MacArthur Communicative Development Inventory, Kern, 2003).

For each target word, an eight-sentence passage was created for the familiarization phase. The target words appeared either towards the beginning (four times) or towards the end (four times) of the sentences (Appendix 1). Mean number of syllables per sentence was 10. To prevent infants from relying on TPs to segment words, syllables preceding and following the target words were always different so that no specific syllabic sequences were repeated within the passages.

The sentences were recorded by a French-native female talker in a sound-attenuated booth. She was asked to produce the sentences with mild IDS (infant-directed speech). The passages lasted 20

Table 1. Target syllables (presented at test) and words corresponding to/containing the target syllables (presented during familiarization) used in Experiments 1–4.

	Words in the familiarization passages	Targets at test
Exp. 1	**dit** [a said]	/di/
	pot [pot]	/po/
	thé [tea]	/te/
	goût [taste]	/gu/
Exp. 2 & 3	**dî**ner [dinner], **di**zain [dizain], **di**van [couch], **di**to [ditto]; cad**die** [caddy], ban**dit** [bandit], tau**dis** [slum], ra**dis** [radish]	/di/
	poney [foal], **po**mmeau [knob], **po**chon [pouch], **po**tin [gossip]; ca**pot** [car hood], dé**pôt** [deposit], to**po** [topo], re**pos** [rest]	/po/
	télé [TV], **te**sson [shard], **tê**tu [stubborn], **té**ton [nibble]; ci**té** [city], pâ**té** [block], syn**thé** [synth], com**té** [county]	/te/
	goulot [neck], **gou**jon [stud], **gou**rou [guru], **gou**da [gouda]; dé**goût** [disgust], ra**gout** [stew], ca**gou** [kagu], ba**gou** [fluency of speech]	/gu/
Exp. 4	**bandit** [bandit]	/bɑ̃di/
	capot [car hood]	/kapo/
	jeté [a throwing]	/ʒøte/
	ragoût [stew]	/ragu/

Table 2. Acoustic measurements of target syllables in passages and in lists for Experiments 1–4.

	Words in passages					Words/syllables in lists			
	Exp. 1	Exp. 2 & 3		Exp. 4		Exp. 1	Exp. 2 & 3	Exp. 4	
	Word	Initial syllable	Final syllable	Initial syllable	Final syllable	Word	Syllable	Initial syllable	Final syllable
Duration (ms)	165	145	161	148	146	358	321	227	273
Intensity (dB)	74.4	74.4	74.8	75.5	75	76.1	74.7	75.1	74.6
Pitch (Hz)	238	215	232	210	228	204	216	226	225

s each. For each syllable, the same talker also produced a list of 20 isolated occurrences for the test phase, which she produced with some variations to avoid infants' boredom and also to evaluate recognition of the targets in a condition with some acoustic variability. The four lists lasted 20 s each. Mean values of syllable duration, intensity and pitch for passages and lists are reported in Table 2.

2.1.3 Procedure, apparatus and design. The experiment was conducted in a sound-attenuated booth, which contained a three-sided test booth made of pegboard panels. The test booth had a red light and loudspeakers (Sony xs-F1722) mounted on each of the side panels and a green light mounted on the central panel. A video camera was situated directly below the centre light to monitor infants' behaviour. A PC computer terminal (Dell Optilex), audio amplifier (Marantz PM4000), TV screen and response box were located outside the sound-attenuated room. The stimuli were stored in digitized form on the computer and were delivered by the loudspeakers via the amplifier. The response box, which was connected to the computer, was equipped with three buttons. The box was controlled by an observer, outside the sound-attenuated booth, who watched the video of the infant on the TV screen and pressed the buttons according to the direction of the infant's headturns, thus starting and stopping the flashing of the lights and the presentation of the sounds. The observer and the infant's caregiver wore earplugs and listened to masking music over tight-fitting headphones, which prevented them from hearing the stimuli. Information about the direction and duration of the headturns/orientation times (OTs) were stored in a data file on the computer.

The variant of HPP set up by Jusczyk and Aslin (1995) was used in the present experiment. Each infant was held on a caregiver's lap and the caregiver was seated in a chair at the centre of the test booth. Each trial began with the green light on the centre panel blinking until the infant had oriented in that direction. Then the centre light was extinguished and the red light above the loudspeaker on one of the side panels began to flash. When the infant made a turn of at least 30° in the direction of the loudspeaker, the stimulus for that trial was played; the red light continuing to flash for the entire duration of the trial. Each stimulus was played to completion or stopped immediately after the infant failed to maintain the 30° headturn for 2 s. If the infant turned away from the red light for less than 2 s and then turned back again, the trial continued but the time spent looking away was not included in the OT. Thus, the maximum OT for a given trial was the duration of the entire speech sample (20 s). If for a trial the infant's OT was shorter than 1.5 s, the trial was immediately replayed from the beginning and the initial OT was discarded.

Each experimental session began with a familiarization phase in which infants heard two passages on alternating trials until they accumulated 30 s of OTs to each. When the infants reached the familiarization criterion for one passage, the second passage continued to be presented until its criterion was also reached. The side of the loudspeaker from which the stimuli were presented was randomly varied from trial to trial. The test phase began immediately after the familiarization criterion was reached. It consisted of three test blocks, in each of which the four lists of isolated syllables were presented. The order of the lists within each block was randomized.

Each infant was familiarized with two passages and tested with the two target and the two control syllables. Each syllable was used as target for half of the infants and as control for the other half.

2.2 Results and discussion

Mean OTs to the lists containing the target versus the control monosyllabic words were calculated for both ages (see Figure 1, left panel). A two-way analysis of variance (ANOVA) with the between-subject factor age (6 versus 8 months of age) and the within-subject factor of familiarity (target versus control) was conducted. The effect of familiarity was significant, $F(1, 38) = 22.1$, $p = .00003$, $\eta^2_p = .368$), indicating that infants had a preference for target ($M = 7.85$ s, $SD = 2.24$) over control ($M = 6.65$ s, $SD = 2.03$) syllables. Moreover, 31 of the 40 infants oriented longer to the familiar lists (binomial test, $p = .0003$). The effect of age and the familiarity × age interaction failed to reach significance (all Fs < 1). Although the factor of familiarity did not interact with the factor of age, we conducted planned comparisons at both ages that confirmed a familiarity effect at both 6, $F(1, 18) = 12.24$, $p = .003$, $\eta^2_p = .405$ and 8, $F(1, 18) = 10.29$, $p = .005$, $\eta^2_p = .364$ months.

By familiarizing French-learning infants for 30 s with passages and testing them with lists of repeated target versus control words, we demonstrated syllabic segmentation effects at both 8 and 6 months of age, thus earlier than previous reports for French (Goyet et al., 2010, 2013; Nazzi et al., 2006, 2014). Our results extend from Spanish and Catalan to French, the finding that 6-month-olds learning a syllable-based language are able to segment monosyllabic words (Bosch et al., 2013). To further explore syllabic segmentation at 6 months in French, in a situation in which

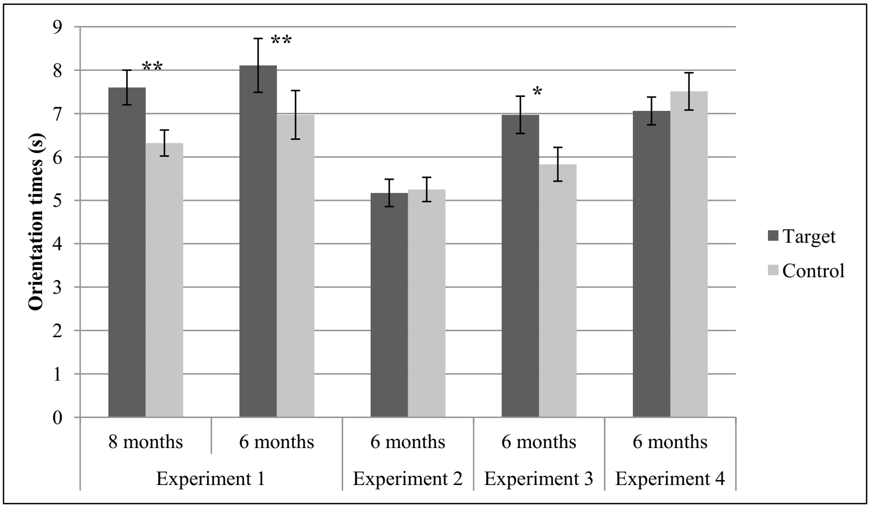

Figure 1. Mean orientation times (and standard errors) to target versus control syllables in Experiments 1–4 (** = p < 0.01; * = p < 0.05).

the syllabic level is distinct from the lexical level, the next experiment replicated Experiment 3 of Goyet et al. (2013), which demonstrated segmentation of syllables embedded in bisyllabic words in French-learning 8-month-olds. Infants were familiarized for 30 s with two passages, each containing eight different bisyllabic words that had in common one target syllable (in word-initial position for half of the words, word-final position for the other half), and then tested on whether they had segmented those syllables by being presented with the two target syllables, and two control syllables.

3 Experiment 2

3.1 Method

3.1.1 Participants. Twenty healthy full-term 6-month-olds were included (10 females and 10 males; mean age: 6 months and 15 days; range: 6 months and 2 days to 7 months and 6 days). Three additional infants were tested but not included due to fussiness (1) or crying (2). All the infants were from monolingual French-speaking families. All parents gave informed consent before participation and completed an information sheet.

3.1.2 Stimuli. We used the same four syllables as in Experiment 1, which have relatively low frequencies, as given in the adult database LEXIQUE 2, in the initial and final positions of French bisyllabic words: /di/ (initial position: 20.47; final position: 3.06); /po/ (initial position: 1.55; final position: 13.65); /te/ (initial position: 7.79; final position: 8.56) and /gu/ (initial position: 3.08; final position: 6.72). For each syllable, eight bisyllabic target words that start (four) or end (four) with that syllable were also chosen for their relatively low frequencies (see Table 1).

As in Experiment 1, an eight-sentence passage was created for the familiarization phase for each target syllable. Again, the target words appeared towards the beginning (four times) or the end (four times) of the sentences, and syllables preceding and following the target words were always different (Appendix 2).

The female talker of Experiment 1 recorded the passages and the four lists of 20 target syllables following the same recording instructions. Mean values of syllable duration, intensity and pitch for passages and lists are reported in Table 2.

3.1.3 Procedure, apparatus and design. The procedure, apparatus and design were identical to Experiment 1.

3.2 Results and discussion

Mean OTs were calculated for the lists containing the target versus the control syllables (see Figure 1, second panel). A paired t-test failed to show a significant difference in OTs to target (M = 5.17 s, SD = 1.41) and control (M = 5.25 s, SD = 1.25) syllables ($t(19) = .101$, $p = .75$). Moreover, only eight of the 20 infants oriented longer to the target syllables (binomial test, $p = .503$).

Experiment 2 fails to provide evidence that French-learning 6-month-olds segment syllables that are embedded in bisyllabic words. These results show that segmenting syllables in bisyllabic words is more demanding than segmenting monosyllabic words (Experiment 1). However, before concluding that French-learning 6-month-olds fail at segmenting syllables in bisyllabic words, contrary to 8-month-olds who succeed in the exact same conditions (Goyet et al., 2013), Experiment 3 was conducted. It replicated Experiment 2 with an increased familiarization time of 45 s (rather than 30 s) to each passage, as done in many studies using the passage-word order (English: Jusczyk & Aslin, 1995; Jusczyk, Houston, et al., 1999; Spanish, Catalan, Spanish/Catalan: Bosch et al., 2013; Canadian French: Polka & Sundara, 2012). This might facilitate segmentation by giving infants more opportunities to hear in context and segment the target syllables.

4 Experiment 3

4.1 Method

4.1.1 Participants. Twenty healthy full-term 6-month-olds were included (11 females and 9 males; mean age: 6 months and 12 days; range: 5 months and 24 days to 7 months and 10 days). Seven additional infants were tested but not included due to fussiness (1), crying (4) or a segmentation index (defined as the difference between the mean OTs to the lists of target and control syllables) more than two SDs above or below the group mean (2). All the infants were from monolingual French-speaking families. All parents gave informed consent before participation and completed an information sheet.

4.1.2 Stimuli, procedure, apparatus and design. The stimuli, procedure, apparatus and design were identical to Experiment 2. The only difference was that familiarization time was 45 s for each passage.

4.2 Results and discussion

Mean OTs were calculated for the lists containing the target versus the control syllables (see Figure 1, third panel). A paired t-test showed a significant preference for target (M = 6.97 s, SD = 1.93) over control (M = 5.83 s, SD = 1.75) syllables ($t(19) = 9.98$, $p = .005$, Cohen's $d = .619$), with 16 of the 20 infants having longer OTs to the target syllables (binomial test, $p = .012$). To compare Experiments 2 and 3, a two-way ANOVA with the factors of experiment and familiarity (target versus control) was conducted. The effect of familiarity was significant, $F(1, 38) = 5.99$, $p = .019$, $\eta^2_p = .136$), indicating that infants had a preference for target (M = 6.07 s, SD = 1.90) over control (M = 5.54 s, SD = 1.53) syllables. The effect of experiment was also significant, $F(1, 38) = 6.63$, $p = .014$, $\eta^2_p = .149$), infants having longer looking times in Experiment 3 than in Experiment 2. Importantly, the familiarity × experience interaction was significant, $F(1, 38) = 7.85$, $p = .008$, $\eta^2_p = .171$), confirming that infants behaved differently in the two experiments, successfully segmenting only with the longer familiarization (Experiment 3). Therefore, the present findings are the first to establish syllabic segmentation at 6 months of age, earlier than previously found for French (Goyet et al., 2010, 2013; Nazzi et al., 2006, 2014), even when the syllabic level does not match the lexical level.

To further investigate the relative order of emergence during development of segmentation of syllabic units (at 6 months in the present study) versus segmentation of bisyllabic words (found at 8 months in Nazzi et al., 2014), we conducted a new experiment with 6-month-olds testing bisyllabic word segmentation. Since successful evidence of segmentation of syllables embedded in bisyllabic words was found in the passage-word order for a familiarization duration of 45 s (Experiment 3) but not 30 s (Experiment 2) to each passage, Experiment 4 tested bisyllabic word segmentation in the same passage-word order using the same (easier) 45 s duration of familiarization.

5 Experiment 4

5.1 Method

5.1.1 Participants. Twenty healthy full-term 6-month-olds were included (8 females and 12 males; mean age: 6 months and 8 days; range: 6 months to 6 months and 21 days). Three additional infants were tested but not included due to crying (2) or a segmentation index (defined as the difference between the mean OTs to the lists of target and control syllables) more than two SDs above or below the group mean (1). All the infants were from monolingual French-speaking families. All parents gave informed consent before participation and completed an information sheet.

5.1.2 Stimuli. We selected four bisyllabic words containing the same four syllables as in Experiment 1, words with relatively low frequencies as given in the adult database LEXIQUE 2: /bɑ̃di/ = 4.59 (*bandit* [bandit]); /kapo/ = 7.23 (*capot* [car hood]); /ʒøte/ = 1.62 (*jeté* [a throwing]) and /ragu/ = 3.65 (*ragout* [stew]). For each word, an eight-sentence passage was created for the familiarization phase. Again, the target words appeared either towards the beginning (four times) or towards the end (four times) of the sentences, had a mean number of syllables per sentence of 11, and syllables preceding and following the target words were always different (Appendix 3).

The sentences were recorded in a sound-attenuated booth by the same French-native female talker as in Experiments 1–3. She was asked to produce the sentences with mild IDS. The passages lasted 20 s each. For each word, the same talker also produced a list of 20 isolated occurrences for the test phase. Mean values of syllable duration, intensity and pitch for passages and lists are reported in Table 2.

5.1.3 Procedure, apparatus and design. The procedure, apparatus and design were similar to Experiments 1, 2 and 3.

5.2 Results and discussion

Mean OTs were calculated for the lists containing the target versus the control words (see Figure 1, right panel). A paired *t*-test failed to show a significant preference for target ($M = 7.06$ s, $SD = 1.44$) over control ($M = 7.51$ s, $SD = 1.93$) words ($t(19) = -1.24$, $p = .23$), with six of the

20 infants having longer OTs to the target words (binomial test, $p = .115$). The present findings fail to establish bisyllabic word segmentation at 6 months of age, under the same test conditions as segmentation of embedded syllables was found in Experiment 3.

To compare Experiments 3 and 4, a two-way ANOVA with the factors of experiment and familiarity (target versus control) was conducted. The effect of familiarity was not significant, $F(1, 38) = 1.79$, $p = .19$), indicating that infants had no preference for targets ($M = 7.01$ s, $SD = 1.68$) over controls ($M = 6.67$ s, $SD = 2.01$). The effect of experiment was not significant, $F(1, 38) = 3.18$, $p = .08$), infants having equal looking times in Experiment 4 ($M = 7.29$ s, $SD = 1.70$) and Experiment 3 ($M = 6.40$ s, $SD = 1.91$). Importantly, the familiarity × experience interaction was significant, $F(1, 38) = 9.6$, p = .004, $\eta^2_p = .202$), confirming that infants behaved differently in the two experiments, successfully segmenting only with the embedded syllable (Experiment 3). Therefore, the present findings provide new evidence regarding the relative developmental order of emergence of segmentation of syllabic units and bisyllabic words in French, establishing an advantage for syllables.

6 General discussion

The main goal of the present segmentation study, using HPP, was to explore French-learning infants' ability to segment syllables from fluent speech in the passage-word order (which provided early segmentation results in recent studies in this language; Goyet et al., 2013; Nazzi et al., 2014), contrasting two conditions: one in which the syllables corresponded to monosyllabic words, and one in which they were embedded in bisyllabic words. Our main goal was to determine French-learning infants' early use of the rhythmic unit of their native language, the syllable, to segment fluent speech. Our findings establish that at 6 months of age, the earliest age at which segmentation has ever been reported in any language, French-learning infants are able to segment both the monosyllabic words (Experiment 1) and the embedded syllables (Experiment 3), therefore demonstrating the early use of syllabic units for segmentation abilities in this language. Moreover, at the same age, and under similar test conditions, we failed to find evidence of bisyllabic word segmentation in French-learning infants (Experiment 4).

The above pattern of results contributes to supporting the early rhythmic segmentation hypothesis stating that infants initially use the rhythmic unit of their native language (the syllable in French) to segment the continuous speech stream (Nazzi et al., 2006) in two ways. Firstly, it shows that at 6 months of age, syllabic units can be segmented by French-learning infants when they correspond to words (Experiment 1), but more importantly also when they are embedded in a longer bisyllabic word (Experiment 3), a condition in which the syllabic and lexical levels are distinct. This extends to 6 months, a similar finding to that of Goyet at al. (2013) with 8-month-olds. Given that at 6 months, Experiment 4 failed to find evidence of bisyllabic segmentation, the present studies confirm the prediction that the ability to segment syllabic units emerges before the ability to segment longer units. Secondly, the comparison of Experiments 3 and 4 establishes that the segmentation of the embedded syllables in Experiment 3 cannot have been the by-product of the segmentation of the eight bisyllabic words that contained these target syllables, since if it were the case, infants should have segmented the target bisyllabic words in Experiment 4. This pattern of findings thus establishes that in terms of processing, French-learning 6-month-olds have access to the rhythmic unit of their native language before accessing larger units. Therefore, the precedence of syllabic segmentation over bisyllabic word segmentation, both in terms of developmental and processing time found here with 6-month-olds, confirms the predictions of the early rhythmic segmentation hypothesis for French (Nazzi et al., 2006).

The present findings also demonstrate that the emergence of segmentation abilities is not delayed in French, contrary to what was suggested by the first studies having explored segmentation in this language (Gout, 2001; Nazzi et al., 2006). Taken together with more recent studies (for Parisian French: Gonzalez Gomez & Nazzi, 2013; Goyet et al., 2013; Nazzi et al., 2014; for Canadian French: Polka & Sundara, 2012), they suggest the emergence of bisyllabic word segmentation between 6 and 8 months of age while pushing down to 6 months the appearance age of syllabic segmentation. It thus appears that using the passage-word order in French allows the observation of early segmentation effects in French, sometimes earlier than using the word-passage order (as found for bisyllabic word segmentation, Nazzi et al., 2014).[1] Furthermore, the present results add to the findings of monosyllabic word segmentation at 6 months in two other syllable-based languages, Spanish and Catalan (Bosch et al., 2013). However, note that in the present study, we only found familiarity effects, while Bosch et al. (2013) observed a switch from a familiarity to a novelty effect between 6 and 8 months. This change was interpreted in relation to the Hunter and Ames' (1988) model as evidence that the task was easier for the older infants. Why we did not find this developmental effect remains to be further explored. Yet, one possibility is that the development of segmentation abilities does not follow the same trajectory/timing in French versus Spanish/Catalan. Another non-exclusive possibility is that the stimuli used in our study were recorded in a less pronounced IDS (as attested by shorter durations and lower pitch in Table 2), which might have made the task slightly more difficult. This possibility is supported by studies having shown a preference for IDS (Fernald & Kuhl, 1987) and starting to show facilitating effects of IDS on early language processing (segmentation: Singh, Nestor, Parikh, & Yull, 2009; Thiessen, Hill, & Saffran, 2005; word learning: Graf Estes & Hurley, 2013).

Importantly, our findings also reveal differences in the ability to segment monosyllabic words and embedded syllables, the former appearing to be easier to segment than the latter. This is demonstrated by the fact that while infants only needed 30 s of familiarization with the passages containing the monosyllabic words, they needed 45 s of familiarization with the passages containing the syllables embedded in bisyllabic words (although the main segmentation effect in the joint analysis of Experiments 2 and 3 suggests the possibility that some infants succeeded to segment in the 30 s condition, even though as a group, the infants failed in that condition). What could explain these differences? Since coarticulation has been found to affect segmentation (Johnson & Jusczyk, 2001), one possibility is that syllables in bisyllabic words are more coarticulated than syllables corresponding to monosyllabic words, and that coarticulation made the recognition more difficult for the more coarticulated syllables. In addition, this effect might have been increased by the fact that half of the embedded syllables corresponded to the first syllables of the words, and half corresponded to the final syllables, with the syllables in initial position being shorter and having lower pitch than both the syllables in final syllables and the syllables corresponding to monosyllabic words (see acoustic measurements in Table 2). Therefore, infants tested with embedded syllables might have had to deal with increased acoustic variation between the different instantiations of the syllables, which is also known from studies on English-learning infants to negatively affect early segmentation (Houston & Jusczyk, 2000; Singh et al., 2009).

In conclusion, the present study brings new evidence in support of the early rhythmic segmentation hypothesis (Nazzi et al., 2006), by establishing syllabic segmentation both for monosyllabic words and embedded syllables, but not bisyllabic words, at 6 months in infants learning a syllable-based language, French (contrary to the trochaic unit segmented by young infants learning stress-based languages). They also indirectly support previous effects of coarticulation, acoustic variation and IDS previously reported to affect segmentation in English-learning infants. Therefore, our study contributes to a better understanding of the similarities and differences in early segmentation across languages, and thus to a better understanding of the mechanisms underlying segmentation.

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Note

1. Nazzi et al. (2014) proposed that the passage-word order advantage found for bisyllabic word segmentation might result from infants processing TP information during familiarization and thus having access to it right from the beginning of the test phase, while, in the word-passage order, it emerges over the trials of the test phase. Note also that there are other possible reasons that disadvantage the word-passage order. For example, in the word-passage order, infants have to go through two simultaneous steps during the test phase (segmentation of the passages; matching of the segmentation outcome to what was heard during familiarization), while during the test phase in the passage-word order, infants "only" have to match the isolated words to the segmentation outcomes from the familiarization phase. Moreover, in the word-passage order, infants hear four passages instead of two in the passage-word order, so that they have to process more syllables/words. Future studies will have to explore more systematically order effects in French and other languages, for different types of words, in order to clarify how these order effects reflect availability and use of cues for segmentation. Note, however, that the passage-word order constitutes a more ecological situation since words are rarely produced in isolation (Brent & Siskind, 2001) and infants have to segment speech streams to extract their first word forms. In that sense, results obtained in the passage-word order might provide a better reflection of early segmentation abilities.

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Appendix 1. Passages used in the familiarization phase of Experiment 1.

/di/ [a said] passage
Ce *dit* énoncé est bien formulé. J'aime quand il narre plusieurs *dits* imagés. Les *dits* annonciateurs du mage sont à craindre. Elles ne relatent que quatre *dits* mensongers. Leurs *dits* ne doivent pas être entendus. J'ai appris quelques *dits* sur lui. Quatre *dits* sont prononcés par la femme. L'homme vocifère de nombreux *dits* contre lui.

/po/ [pot] passage
Trois *pots* bleus sont bien suffisants. Je mets quelques pivoines dans ce *pot* vert. Quelques *pots* en grès sont en vente. J'aimerais trouver quatre *pots* dans le jardin. Mes *pots* rouges en terre sont cassés. Il recycle ses *pots* contenant certains cornichons. Vos *pots* de yaourt se recyclent. Au marché cinq *pots* d'olive sont offerts.

/te/ [tea] passage
Le *thé* est une boisson savoureuse. Le matin je bois du *thé* au lait. Boire deux *thés* me réveille plus facilement. Je ne consomme que certains *thés* anglais. Certains *thés* sentent vraiment très bon. Ma fille aime sucrer son *thé* vert. Certains *thés* ne se trouvent qu'au marché. Tu n'achètes que ton *thé* en boîte.

/gu/ [taste] passage

Le *goût* de ces cerises m'enchante. La fille n'aime pas le *goût* sucré. Ces *goûts* exquis et savoureux me plaisent. L'enfant se régale au *goût* de la crème. Mon *goût* préféré est celui de la menthe. L'alimentation varie selon les *goûts* de chacun. Nos *goûts* favoris sont le citron et le café. Au fur et à mesure nos *goûts* évoluent.

Appendix 2. Passages used in the familiarization phase of Experiments 2 and 3.

/di/ passage
Le *dîner* mondain m'ennuie horriblement. Leurs *caddies* contiennent beaucoup de denrées. Il lui a écrit un *dizain* romantique. Il vient d'arrêter cinq *bandits* dangereux. Tes deux *divans* rouges sont très confortables. Votre *taudis* vient d'être découvert. L'homme doit écouter deux *ditos* moralisants. J'aime manger ces deux *radis* salés

/po/ passage
Vos *poneys* broutent dans le près. Quelques *capots* rouges sont froissés. Les filles raffolent de *potins* crapuleux. Les meubles sont rangés dans un *dépôt* scellé. Ton *pommeau* de douche est cassé. Notre *topo* a convaincu l'assemblé. J'ai remplis notre *pochon* de cerises. J'ai besoin de plus de *repos* en hiver.

/te/ passage
Trop de *télé* abrutit les enfants. J'habite près des *cités* des arts. J'ai marché sur un *tesson* de bouteille. J'ai acheté trois *pâtés* en croute. Quelques *têtus* sont dans cette classe. Le *synthé* lui sera offert à noël. Les veaux boivent aux *tétons* de leurs mères. Il existe quatre *comtés* dans la région.

/gu/ passage
Le *goulot* de la bouteille est brisé. Notre *dégoût* de la viande est surmonté. Il prépare un *goujon* citronné. Elle déguste ce bon *ragoût* cuisiné. Quelques *gourous* les influencent dangereusement. Les *cagous* ont des plumes argentées. Vous découpez des tranches de *gouda* salé. Vous trouvez parfois que son *bagou* dérange.

Appendix 3. Passages used in the familiarization phase of Experiment 4.

/ bɑ̃di / passage
Le *bandit* appelait ses complices barbus. Je me défendais contre des *bandits* verts. Ces *bandits* ont braqué les bijouteries. Tu as rencontré un *bandit* aimable. Certains *bandits* font amende honorable. Les policiers cherchaient plusieurs *bandits* rouges. Quelques *bandits* se sont précipités dehors. L'avocat écoute les *bandits* repentis.

/kapo/ passage
Ce *capot* ne s'ouvre que de l'arrière du véhicule. Nous réparerons demain un *capot* troué. Des *capots* s'entassent par centaine de milliers. Vous allez certainement croiser le *capot* bleu. Notre *capot* laisse sortir beaucoup de fumée. J'ai admiré ce matin ces *capots* neufs. Plusieurs *capots* ont été envoyés à la casse. Tu leur aurais envoyé trois *capots* lustrés.

/ ʒøte / passage
Ce *jeté* a battu le précédent record. Ils n'esquiveront jamais nos *jetés* francs. Des *jetés* ont permis l'obtention de droits. Nous recevrons de plein fouet le *jeté* direct. Certains *jetés* arrivent à dépasser la ligne. Vous allez me filmer ces *jetés* longs. Quelques *jetés* pleuvent encore au-dessus. Je calcule la vitesse d'un *jeté* droit.

/ragu/ passage
Le *ragoût* de ma grand-mère est délicieux. Le cuisinier mijote les *ragoûts* salés. Ce *ragoût* me replonge en petite enfance. Leur préférence ira au *ragoût* sucré. Ces *ragoûts* laissent un souvenir mémorable. Les sans-abris mangent quelques *ragoûts* chauds. Votre *ragoût* est digne d'apparaître à l'Elysée. Je tomberai sur certains *ragoûts* amers.