Effects of Prior Phonotactic Knowledge on Infant Word Segmentation: The Case of Nonadjacent Dependencies

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\textbf{Purpose:} In this study, the authors explored whether French-learning infants use nonadjacent phonotactic regularities in their native language, which they learn between the ages of 7 and 10 months, to segment words from fluent speech.

\textbf{Method:} Two groups of 20 French-learning infants were tested using the head-turn preference procedure at 10 and 13 months of age. In Experiment 1, infants were familiarized with 2 passages: 1 containing a target word with a frequent nonadjacent phonotactic structure and the other containing a target word with an infrequent nonadjacent phonotactic structure in French. During the test phase, infants were presented with 4 word lists: 2 containing the target words presented during familiarization and 2 other control words with the same phonotactic structure. In Experiment 2, the authors retested infants’ ability to segment words with the infrequent phonotactic structure.

\textbf{Results:} Ten- and 13-month-olds were able to segment words with the frequent phonotactic structure, but it is only by 13 months, and only under the circumstances of Experiment 2, that infants could segment words with the infrequent phonotactic structure.

\textbf{Conclusion:} These results provide new evidence showing that infant word segmentation is influenced by prior nonadjacent phonotactic knowledge.

\textbf{Key Words:} language acquisition, word segmentation, phonotactics, labial–coronal bias, French

From birth, infants are immersed in speech, hearing thousands of utterances that do not include systematic marks of where word boundaries are. Therefore, in order to learn the words of their native language, infants have to solve a very challenging task; that is, they have to discover what is and what is not a wordlike unit. Years of research have shown that to start finding word boundaries, very early in life, infants exploit different phonological regularities of their language. In the present study, we contribute to this research by exploring infants’ use of nonadjacent phonotactic knowledge.

A first cue that has been found to play a particularly important role for word segmentation is \textit{transitional probabilities} (TPs)—that is, the normalized version of the probability of event Y given event X (TP \[ Y/X \] = frequency of XY/frequency of X), which is used as early as 6–8 months of age in English, Dutch, and French (Johnson & Tyler, 2010; Mersad & Nazzi, 2012; Saffran, Newport, & Aslin, 1996). A second important cue relates to prosodic regularities and more precisely rhythmic units like the trochaic unit for stressed-based languages such as English or Dutch (Echols, Crowhurst, & Childers, 1997; Houston, Jusczyk, Kuijpers, Coolen, & Cutler, 2000; Jusczyk, Houston, & Newsome, 1999; Kooijman, Hagoort, & Cutler, 2009; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel, & Jusczyk, 2005), or the syllabic unit for syllable-based languages such as French (Goyet, de Schonen, & Nazzi, 2010; Goyet, Nishibayashi, & Nazzi, 2013; Mersad, Goyet, & Nazzi, 2010; Nazzi, Iakimova, Bertone, Frédonie, & Alcantara, 2006; Nazzi, Mersad, Sundara, Iakimova, & Polka, 2013; Polka & Sundara, 2012), which are used for segmentation by 8 months of age at the latest. Third, \textit{allophonic variations}—that is, the fact that some phonemes are pronounced in a different way depending on their position in the word—have also been found to impact word segmentation by 10.5 months of age (Jusczyk, Hohne, & Baumann, 1999).

A fourth cue to early word segmentation, which is explored in the present study, \textit{is phonotactic knowledge}, which refers to regularities regarding the legality or frequency of sequences of phonemes that are allowed in the words of a given language. In a first study, Mattys, Jusczyk, Luce, and Morgan (1999) found that at 9 months, infants are already
sensitive to the way in which phonotactic sequences (cross syllabic C-C clusters)\(^1\) typically align with word boundaries in their native language, which affects their preferences for bisyllabic sequences. In a subsequent study, Mattys and Jusczyk (2001b) established that the probability of appearance of clusters within words or at word boundaries also affects the way in which infants segment words out of fluent speech. Mattys and Jusczyk’s results establish a segmentation advantage for words presented in a phonotactic context in which they are surrounded by high-probability between-word clusters, suggesting that 9-month-old infants use adjacent phonotactic information to find word boundaries.

The above studies thus establish that prior phonotactic knowledge influences segmentation by as early as 9 months in English-learning infants. In the present study, first we go beyond these findings by extending the evidence to infants learning another language: French. Second, and more important, we explore whether infants can use not only adjacent phonotactics, as demonstrated by Mattys and Jusczyk (2001a, 2001b), but also nonadjacent dependencies. Demonstrating such an extension would be important because languages instantiate both adjacent and nonadjacent regularities. Adjacent regularities correspond to dependencies between two or more elements that occur continuously. For example, English allows some consonant clusters but not others: the sound / interfaces at the beginning of a syllable can be followed by /l/, /n/, or /m/. Nonadjacent regularities refer to dependencies between two or more elements that are separated by other elements, thus occurring discontinuously. For example, in Semitic languages such as Hebrew and Arabic, families of words correspond to consonantal roots, such as k-t-b for writing, and variations in vowel identity indicate lexical class, number, and gender (Ryding, 2005). Nonadjacent dependencies are an important feature of natural languages, given that languages make an extensive use of nonadjacent/distant dependencies (cf. Gonzalez-Gomez & Nazzi, 2012, for a more detailed discussion of these issues).

At the phonological level, research on adults has established that a nonadjacent cue, vowel harmony, can be used for segmentation by adults (Suomi, McQueen, & Cutler, 1997; Vroomen, Tuomainen, & de Gelder, 1998). Although never investigated before, the possibility of finding an effect of nonadjacent dependencies on early word segmentation is rendered likely by recent findings showing infants’ acquisition of nonadjacent phonotactic knowledge at the same age as they acquire adjacent knowledge.

Regarding adjacent phonotactic dependencies, research has established that they are acquired early in life, as evidenced by the fact that between 6 and 9 months of age, infants start preferring the phonotactic patterns of their native language. English- and Dutch-learning 9-month-olds listen longer to phonemic sequences legal in their native language than to illegal ones (Friederici & Wessels, 1993; Jusczyk, Cutler, & Redanz, 1993), whereas 6-month-olds do not have a preference. A similar developmental pattern was found for Spanish–Catalan bilingual infants (Sebastián-Gallés & Bosch, 2002). Infants learning various languages, therefore, become sensitive to the legality of adjacent sound sequences in their native language by 9–10 months. Furthermore, they have also been found to become sensitive to the relative probability of occurrence of adjacent sound sequences at the same age—9-month-old English-learning infants prefer to listen to high-probability than low-probability phonotactic sequences (Jusczyk, Luce, & Charles-Luce, 1994). All these findings establish that infants have become sensitive to the phonotactic patterns of their native language occurring between adjacent elements by 10 months of age.

More recently, two perceptual studies on the labial–coronal (LC) bias have shown that infants also become sensitive to nonadjacent phonological dependencies by 10 months of age (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009). The LC bias was initially reported in young English and French children’s early productions, with findings that they produce more LC words (i.e., sequences of sounds containing first a labial consonant followed by a coronal consonant, such as /beta/) than words with the opposite coronal–labial (CL) pattern (i.e., sequences of sounds containing first a coronal consonant followed by a labial consonant, such as /tipi/; e.g., Ingram, 1974; MacNeilage, Davis, Kinney, & Matyear, 1999). The LC bias was first interpreted in terms of production constraints, according to which producing an LC sequence requires fewer and easier movements than producing a CL sequence (Ingram, 1974; MacNeilage & Davis, 2000). However, given that in many languages, including English and French, LC words are much more frequent than CL words (Gonzalez-Gomez & Nazzi, 2012; MacNeilage & Davis, 2000; Vallée, Rousset, & Boë, 2001), Nazzi and colleagues explored a perceptual explanation for the emergence of the LC bias (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009). Accordingly, they found that 10- but not 6-month-old infants prefer to listen to LC words than to CL words even before they start producing LC and CL sequences (Gonzalez-Gomez & Nazzi, 2012). These findings establish that the LC bias cannot be only due to motor constraints but that this bias also reflects some perceptual learning of input regularities (which might indirectly reflect articulatory constraints; for further evidence, see data on Japanese adults and infants; Gonzalez-Gomez, Tsuji, Hayashi, Mazuka, & Nazzi, 2013; Tsuji, Gonzalez Gomez, Medina, Nazzi, & Mazuka, 2012).

Importantly, 10-month-olds’ preference for the LC pattern was taken as evidence of nonadjacent phonotactic acquisition. This conclusion was reached, first, on the basis that the LC bias is considered a nonadjacent phonotactic dependency because it involves a relation between two consonants separated by a vowel. Second, the fact that infants were reacting to the relative position of the nonadjacent consonants is further supported by the fact that in Gonzalez-Gomez and Nazzi (2012), all the adjacent frequencies of the stimuli were fully controlled, leaving only an overall nonadjacent frequency advantage for the LC

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\(^1\)The “dot” (‘‘·’’) in “C-C” indicates a syllable boundary within a word.
structure over the CL structure, whereas the frequencies of the sound sequences used as stimuli were equated across the two structures. Third, this conclusion is also supported by the two control experiments conducted by Gonzalez-Gomez and Nazzi (2012), which showed that the LC preference found at 10 months was not due to a labial word-initial bias or a coronal word-final bias.

Following the above findings, we explored in the present study whether infants can use their nonadjacent phonotactic knowledge to find word forms in fluent speech. Before presenting the experiments that were conducted to address this issue, we report the results of a prior analysis that guided the design of the experiments for the present study. This analysis was conducted on a corpus of speech addressed to infants (corpus by Karine Martel, Université de Caen Basse-Normandie) in order to verify the distribution in infants’ input of LC and CL sequences and how they relate to words and word boundaries. The corpus contains the recordings of 10 mothers interacting with their infants ($M_{age} = 7$ months $24$ days; range = $5$ months $8$ days to $10$ months $22$ days; five girls, five boys). Recordings were made at their home while the mother was interacting with the infant. Recording duration varies from one dyad to another ($M_{duration} = 16$ min, range = $9$–$24$ min). The corpus contains 6,673 word tokens, corresponding to 2,524 unique word tokens. The number of times that LC and CL sequences appear. Following previous studies (MacNeilage et al., 1999; Vallée et al., 2001), we only counted LC and CL consonant pairs that were separated by one and only one vowel. Then, each pair was classified for counting purposes as appearing either in intrasyllabic (i.e., /-tu-vamɔ 3elapat/) or intersyllabic (i.e., /-tu-vamɔ 3elapat/), position, and as appearing either within words (i.e., /-tu-vamɔ 3elapat/) or between words (i.e., /-tu-vamɔ 3elapat/). It is important to note that due to the “one and only one vowel” constraint, intrasyllabic counts included relations between an onset and a coda (e.g., /pat/) but excluded relations within clusters (e.g., /pla/) or between the onset of a cluster and the following coda (e.g., /pret/). Moreover, intersyllabic counts only included sequences between the onset consonants of two adjacent syllables, the first one being a CV syllable (e.g., /lapat/).

Table 1. Total number of labial–coronal (LC) and coronal–labial (CL) sequences observed within words and between words in the Martel corpus.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Within words</th>
<th></th>
<th>Between words</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intersyllable</td>
<td>Intrasyllable</td>
<td>Total</td>
<td>Intersyllable</td>
</tr>
<tr>
<td>LC</td>
<td>240</td>
<td>97</td>
<td>337</td>
<td>237</td>
</tr>
<tr>
<td>CL</td>
<td>67</td>
<td>9</td>
<td>76</td>
<td>750</td>
</tr>
</tbody>
</table>

$^a$No intrasyllabic between-word sequences were found—such sequences would occur only through liaison-based resyllabification between two words, the second one being vowel-initial.

Lastly, a sequence/word like /demɔl/ was counted as contributing both an LC occurrence (/demɔ/) and a CL occurrence (/demɔl/).

A first way of analyzing the results (cf. Table 1) is to look at the relative frequency of occurrence of LC and CL sequences within words and across words (column analysis). This comparison shows that when comparing the LC and CL sequences of the corpus, LC sequences are much more frequent than CL sequences within words, both for intersyllabic sequences (78% LC vs. 22% CL) and intrasyllabic sequences (92% LC vs. 8% CL). However, CL sequences occur more frequently than LC sequences between words (76% CL vs. 24% LC). Therefore, LC sequences appear to have high within-word frequencies and low between-word frequencies, whereas CL sequences have high between-word frequencies and low within-word frequencies. From these patterns, it appears that wordlike units are likely to be LC sequences, whereas word boundaries are more likely to correspond to CL sequences. Note that this pattern is unlikely to be the sole result of the specific objects that the mothers were naming. Indeed, 21 objects were named by the mothers, corresponding to the objects and images brought by the experimenter (pomme, bouchon, livre, coccinelle, marionnette, girafe, winnie, mouton, lapin, clown, velo, telephone, chat, ballon, fleur, poupée, herisson, abeille, escargot, nounours). These names contained an LC sequence 31.8% of the time, a CL sequence 22.7% of the time, and neither LC nor CL sequences the remaining 45.5%. This ratio of 1:4 (i.e., 58.3% LC vs. 41.7% CL) in favor of LC sequences is similar to the one found in the French lexicon (1:68; cf. Gonzalez-Gomez & Nazzi, 2012) and lower than the counts observed in the mothers’ speech to their infants.

A second way to analyze the data presented in Table 1 is to determine whether finding an LC or CL sequence would allow predicting whether that sequence is part of a word or spans a word boundary (row analysis). These comparisons show that 59% of LC sequences appear within words, whereas 91% of CL sequences appear at word boundaries. Therefore, if infants assumed that every LC sequence appears within a word, they would be right almost 60% of the time, and if they assumed that every CL sequence marks a word boundary, they would be right more than 90% of the time. Therefore, knowledge of these nonadjacent phonotactic properties of French could help French-learning infants to segment wordlike units from fluent speech.

In light of these findings, we explore in the present study whether infants are using LC and CL sequences to
retrieve word forms and word boundaries from fluent speech. Experiment 1 was conducted to compare French-learning infants’ ability to segment from fluent speech words with high within-word frequencies and low between-word frequencies (LC words) and words with low within-word frequencies and high between-word frequencies (CL words). On the basis of the literature on the impact of adjacent phonotactic knowledge on early word segmentation, we predicted better performance for LC words. Two groups of infants were tested, at 10 and 13 months of age. These ages were selected given the studies reviewed above showing that French-learning infants become sensitive to these LC/CL nonadjacent phonological dependencies by 10 months (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009), so that effects of such acquisition on segmentation are expected to be found at or after 10 months. Infants were tested using the procedure set up by Jusczyk and Aslin (1995), in which infants are familiarized with passages containing target words and then tested on their recognition of these words. Segmentation is attested classically by a preference for target over control words at test.

**EXPERIMENT 1**

**Method**

**Participants**

Forty infants from French-speaking families were tested: twenty 10-month-olds (Mage = 10 months 15 days; range = 10 months 5 days to 10 months 24 days; eight girls, 12 boys) and twenty 13-month-olds (Mage = 13 months 18 days; range = 13 months 6 days to 13 months 28 days; 12 girls, eight boys). The data of three additional 10-month-olds and two additional 13-month-olds were not included in the analyses due to fussiness/crying (n = 5).

**Stimuli and Design**

**Familiarization stimuli.** Four different passages containing eight sentences were used. Sentences within passages were semantically unrelated. In each sentence of a given passage, the same LC or CL target word appeared once, never in sentence-initial or final position. Each passage was associated with an LC sequence and with a CL sequence across conditions, meaning that each passage was used for both LC and CL target words across subjects (see the Appendix).

In each age group, infants were divided into four subgroups (conditions) and were familiarized with one of four possible pairs of target passages (/butl/–/dip/, /pid/–/tub/, /poet/–/tub/, and /bod/–/tcep/). Each infant was familiarized with two passages: one containing an LC target word and a second one containing a CL target word. Each word was used an equal number of times as target and control across infants.

**Test stimuli.** Eight monosyllabic Cons1Vow1Cons2 pseudowords were selected, combining labial consonants /p/ and /b/ and coronal consonants /t/ and /d/: four items with an LC structure (one bVd: /bod/; one pVt: /poet/; one bVt: /but/; and one pVd: /pid/) and four items with a CL structure (one dVb: /dab/; one tVp: /tcep/; one tVb: /tub/; and one dVp: /dip/).

Items in both lists were made up of exactly the same consonants and vowels. As in Gonzalez-Gomez and Nazzi (2012), vowels were chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the Cons1Vow1, Vow1Cons2, and Cons1Vow1Cons2 sequences of phonemes according to the Lexique 3 database (New, Pallier, Ferrand, & Matos, 2001). This was done to ensure that infants react to the overall relative position of the nonadjacent consonants (the overall predominance of LC structures) and not to the relative frequency of the LC and CL sequences used as stimuli (which were equated).

All the stimuli were recorded in a sound-attenuated booth by a French female native speaker who was naive to the hypotheses of the study. Twenty different tokens of each word were selected to create eight word lists: four LC lists (one for each of the four LC words) and four CL lists (one for each of the four CL words). The duration of all the word lists and passages was 20 s.

**Procedure and Apparatus**

The experiment was conducted inside a sound-attenuated room, in a booth made of pegboard panels (bottom part) and a white curtain (top part). The test booth had a red light and a loudspeaker (SONY xs-F1722) mounted at eye level on each of the side panels and a green light mounted on the center panel. Below the center light was a video camera used to monitor infants’ behavior.

A PC computer (Dell Optiplex), a TV screen connected to the camera, and a response box were located outside the sound-attenuated room. The response box, connected to the computer, was equipped with a series of buttons. The observer, who looked at the video of the infant on the TV screen to monitor the infant’s looking behavior, pressed the buttons of the response box according to the direction of the infant’s head, thus stopping and starting 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 closed headphones, which prevented them from hearing the stimuli presented.

We used the version of the Head-Turn Preference Procedure set up by Jusczyk and Aslin (1995) using the passage-word order. Each infant was held on a caregiver’s lap in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented to it. Then, the red light on one of the side panels began to flash. When the infant turned in that direction, the stimulus for that trial began to play. The stimuli were delivered by the loudspeakers via an audio amplifier (Marantz PM4000). Each stimulus was played to completion or stopped immediately after the infant failed to maintain the head turn for 2 consecutive seconds. If the infant turned away from the target by 30° in any direction for less than 2 s and then turned back again, the trial continued, but the time spent looking away (when the experimenter released the buttons of the response box) was automatically subtracted from the orientation time by the program. Thus, the
maximum orientation time for a given trial was the duration of the entire speech sample. If a trial lasted less than 1.5 s, the trial was repeated, and the original orientation time was discarded. Information about the duration of the head turn was stored on the computer.

Each experimental session began with a familiarization phase containing two different passages, one with an LC target and one with a CL target. Within each passage, each target word was repeated eight times. Passages were presented in random order until infants accumulated 30 s of listening time to each. The test phase consisted of two test blocks, each corresponding to the presentation of four different lists: two lists containing the two target words presented during the familiarization phase (Target LC, Target CL) and two lists containing two novel/control words (Control LC or Control CL). The order of presentation of the four lists within each block was randomized.

**Results and Discussion**

Orientation times to the familiar and the control lists were calculated for each infant and averaged across infants within each group: 10-month-olds ($M_{\text{target}} = 7.57$ s, $SD = 1.62$ s; $M_{\text{control}} = 6.24$ s, $SD = 1.65$ s) and 13-month-olds ($M_{\text{target}} = 9.10$ s, $SD = 3.03$ s; $M_{\text{control}} = 6.01$ s, $SD = 2.01$ s; cf. Figure 1). A three-way analysis of variance (ANOVA), with the between-subjects factor of age (10 months vs. 13 months) and the within-subjects factors of familiarity (target vs. control) and lexical structure (LC vs. CL), was conducted. The effect of familiarity was significant, $F(1, 76) = 27.84$, $p < .001$, $\eta^2_p = .27$, with infants having longer orientation times to target than to control lists. The effect of lexical structure was also significant, $F(1, 76) = 41.85$, $p = .048$, $\eta^2_p = .046$, with infants having longer orientation times to LC than to CL lists. In addition, the interaction between familiarity and age was significant, $F(1, 76) = 4.44$, $p = .04$, $\eta^2_p = .06$. This was due to the fact that the difference between target and control words was greater for the 13-month-olds (3.10 s) than for the 10-month-olds (1.23 s). More importantly, the interaction between familiarity and lexical structure was also significant, $F(1, 76) = 13.24$, $p < .001$, $\eta^2_p = .15$, suggesting that the effect of familiarity was different for the two lexical structures. Planned comparisons showed that the familiarity effect was not significant in the CL condition at either age: 10-month-olds, $F(1, 76) = 0.25$, $p = .61$; 13-month-olds, $F(1, 76) = 1.27$, $p = .26$; whereas the effect was significant in the LC condition at both ages: 10-month-olds, $F(1, 76) = 7.07$, $p = .009$, $d = 0.84$; 13-month-olds, $F(1, 76) = 39.15$, $p < .001$, $d = 1.56$. All other effects and interactions failed to reach significance.

On the basis of the familiarity effects observed, Experiment 1 shows that 10- and 13-month-old infants are able to segment the LC words but fails to provide evidence that they are segmenting the CL words. It is important to remember that in French, LC sequences are much more frequent word-internally than CL sequences and that

![Figure 1. Mean orientation times to the target versus control words for both conditions averaged together (overall): the labial–coronal (LC) condition and the coronal–labial (CL) condition. Errors bars represent the standard error of the mean.](image)
10-month-olds prefer to listen to lists of LC words over CL words (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009), suggesting that they have acquired this phonotactic property of French words. Therefore, there are at least two possible explanations for the failure in the CL condition. The first is that 10- and 13-month-olds are not able to segment CL sequences given that these structures have a low within-word frequency and a high between-words frequency, a pattern associated with word boundaries. A second possibility is that 10- and 13-month-old French infants are actually able to segment the CL sequences, but we were not able to show this in Experiment 1 due to a competition effect, given that LC and CL structures were both presented during the test. As a result, the LC structures, predominant in French, might have attracted infants’ attention, interfering with the processing of the CL ones. This possibility is suggested by the overall longer orientation times to the LC words found in the test phase.

In order to evaluate these possibilities, two new groups of 10- and 13-month-olds were tested in Experiment 2. In this new experiment, only the CL stimuli from Experiment 1 were used. This manipulation removed the potential competition effect by presenting LC and CL words together. Thus, if 10- and 13-month-old infants were able to segment the CL sequences, but this effect was masked by the competition effect, then in Experiment 2, which removes this possible competition effect, 10- and 13-month-olds should show evidence of segmenting CL sequences. By contrast, if they were not able to segment the CL sequences, no such effect should be found in Experiment 2 either.

## EXPERIMENT 2

### Method

#### Participants

Forty infants from French-speaking families were tested: twenty 10-month-olds ($M_{age} = 10$ months 10 days; range = 10 months 2 days to 10 months 24 days; 10 girls, 10 boys) and twenty 13-month-olds ($M_{age} = 13$ months 11 days; range = 13 months 1 day to 13 months 25 days; 11 girls, nine boys). The data of three additional 10-month-olds and two additional 13-month-olds were not included in the analyses due to fussiness/crying ($n = 5$).

#### Stimuli and Design

All the CL stimuli from Experiment 1 were used. In each age group, half the infants were familiarized with passages containing the target words /tub/ and /dzh/, and the other half with passages containing the target words /dip/ and /teep/.

#### Procedure and Apparatus

The procedure and apparatus were the same as those used in Experiment 1, except that infants heard only CL targets.

### Results and Discussion

Mean orientation times to the familiar and control lists were calculated for each infant. The data for the 10-month-olds ($M_{target} = 7.29$ s, $SD = 2.86$ s; $M_{control} = 7.72$ s, $SD = 3.39$ s) and for the 13-month-olds ($M_{target} = 7.23$ s, $SD = 2.74$ s; $M_{control} = 5.61$ s, $SD = 1.80$ s) are presented in Figure 2. A two-way ANOVA, with the between-subjects factor of age (10 vs. 13 months) and the within-subject factor of familiarity (familiar vs. control words), was conducted. The familiarity effect was not significant, $F(1, 38) = 1.68$, $p = .20$. The effect of age also failed to reach significance, $F(1, 38) = 2.14$, $p = .15$. However, the interaction between age and familiarity was significant, $F(1, 38) = 4.98$, $p = .03$, $\eta_p^2 = .11$, indicating that the effect of familiarity changed with age. Planned comparisons showed that the lexical structure effect was nonadjacent at 10 months, $F(1, 38) = 0.43$, $p = .51$, but was significant at 13 months, $F(1, 38) = 6.23$, $p = .01$, $d = 0.69$. These results again fail to show that 10-month-old infants are able to segment CL sequences.

Taken together with the results of Experiment 1, the present results establish that 10-month-old infants are not able to segment the low within-word frequency and high between-word frequency CL words. Therefore, it appears that 10-month-olds’ failure in Experiment 1 was not due to a competition effect in the test phase. However, by 13 months, infants are able to segment the CL words. Therefore, it seems that the failure of the 13-month-olds with CL words in Experiment 1 was due to a competition effect related to the presentation of both LC and CL words. Hence, our findings reveal developmental changes between 10 and 13 months of age, indicating that during this period, infants become able to segment words having high between-word frequencies and low within-word frequencies.

### GENERAL DISCUSSION

The goal of the present study was to explore whether prior knowledge of the probability of nonadjacent sound structures impacts infants’ word segmentation. To explore this issue, we investigated when French-learning infants start segmenting LC structures that are very frequent word-externally compared with CL structures that are less frequent word-externally in French. The results of two experiments show that infants are able to segment LC structures at least by 10 months of age but that, in similar (Experiment 1) or easier (Experiment 2) experimental conditions, they are not able to segment the opposite CL pattern until a few months later, by 13 months of age. The present study brings new evidence showing that infant segmentation of fluent speech is affected by the relative frequency of nonadjacent phonological dependencies.

These results thus confirm that infants are sensitive to nonadjacent phonological dependencies, as previously shown (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009). More importantly, they show that nonadjacent phonological dependencies can be useful for processes related to early lexical acquisition.
Note that the present study does not directly allow us to specify that the LC advantage is linked to the fact that infants segmented and recognized target LC words/word forms more easily than target CL words/word forms, rather than recognizing target LC sequences more easily than target CL sequences. To directly demonstrate this, one would have to show that this effect is linked to the lexical status of the target sequences and that a different pattern would be found if the same sequences did not correspond to a word—that is, if they straddled a word boundary. However, this lexical implication is indirectly supported by data of English-learning infants showing that at 8.5 months, they fail to recognize a CVC sequence that straddles a word boundary (dice produced as cold ice; Mattys & Jusczyk, 2001a).

Importantly, though, note that no matter whether the lexical level is implicated, it remains that the early LC segmentation advantage would have the consequence of allowing infants to segment more LC than CL sequences, which could then be linked to concepts to form lexical entries (as recently shown by Gonzalez-Gomez, Poltrock, & Nazzi, 2013). Infants would thus learn more LC words, which would clearly be appropriate for lexical acquisition in French, given the predominance of LC over CL words in that language (ratio of 1:68; cf. Gonzalez-Gomez & Nazzi, 2012).

Going back to the difference in performance between LC and CL structures, there are at least two factors that might explain our finding that the LC words were easier to segment than the CL words in our study. The first one is that LC sequences have a frequent phonotactic structure. Because it has been shown that 10-month-old infants have a preference for these structures (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009), it is possible that structure typicality played a role in the recognition of these structures. As argued by Jusczyk et al. (1994), frequent phonotactic structures are likely to be more easily recognized and, consequently, more easily segmented. The second factor is revealed by our corpus analysis, showing that LC sequences are not only more frequent in the French lexicon (Gonzalez-Gomez & Nazzi, 2012; MacNeilage & Davis, 2000; Vallée et al., 2001), but they also have a high within-word frequency and a low between-words frequency—a frequency pattern associated with wordlike units.

The two factors that facilitated the segmentation of the LC words can also explain our findings that CL words were not segmented by 10, but only by 13, months of age. First, CL sequences are much less frequent word-internally than LC ones. Second, CL sequences have low within-word frequencies and high between-word frequencies; this pattern is usually associated with word boundaries. It is important to remember that in the Martel corpus, 90% of CL sequences were found between words. If 10-month-olds have discovered that CL sequences mostly occur at word boundaries, it is possible that they treat CL sequences as being part of two different words, thus missegmenting CL words. This effect would be transitory because by 13 months, infants are able to segment the CL words. This possibility of transitory mis-segmentation is in line with Jusczyk, Houston, and Newsome’s (1999) results showing that 7.5-month-old English-learning infants are able to segment words containing a strong/weak stress pattern, which is the most common
pattern in their native language, but that they missegment words having a weak/strong stress pattern, to match it up with the common strong/weak pattern (i.e., “guitar” is segmented as “taris”). Three months later, at 10.5 months, infants are also able to segment weak/strong words, probably by relying on other segmentation cues. The pattern found in our study on phonotactics is thus similar to the pattern that was found in the Jusczyk, Houston, and Newsome (1999) study on prosody.

Although missegmentation of the CL words is a possibility, the structure of our stimuli makes this possibility unlikely. First, our targets are monosyllabic CVC words, and syllables have often been thought of as good segmentation units (Eimas, 1997; Jusczyk, Goodman, & Baumann, 1999; Mehler, Dupoux, & Segui, 1990), in particular for French (Goyet et al., 2010, 2013; Nazzi et al., 2006, 2013; Polka & Sundara, 2012). Second, in our study, target words were followed by a consonant-initial word in 78% of the sentences (i.e., /sɛʁɛt tɯ bɔ bje meri/). As a consequence, missegmenting the CL sequences by placing a word boundary between the two consonants would produce consonant clusters, and an analysis of these clusters showed that these would be illegal or very rare within-word clusters in French more than 50% of the time (i.e., /sɛʁɛtɛtu bɔs/). Because Mattys and colleagues (Mattys et al., 1999; Mattys & Jusczyk, 2001b) have shown that infants are already sensitive to cluster probabilities at word boundaries by 9 months of age, in both onset and coda positions, such segmentation is unlikely to have happened. Therefore, a further possibility is that the presence of conflicting cues led to the non-segmentation of the portion of speech around the CL words. Further research is needed to explore these and other possible explanations.

In summary, the findings of the present study extend the evidence in the literature showing that English-learning infants are able to use phonotactic cues to segment fluent speech (Mattys & Jusczyk, 2001b; Mattys et al., 1999) to French-learning infants. Moreover, our results extend the existing evidence about the influence of prior phonotactic knowledge on word-form segmentation, from the use of adjacent regularities to the use of nonadjacent dependencies. They also provide further evidence for a link between early speech perception/phonological acquisition and word-form segmentation, as previously shown for prosodic cues (phonological acquisition: Jusczyk et al., 1993; word segmentation: Jusczyk, Houston, & Newsome, 1999), allophonic cues (phonological acquisition: Hohne & Jusczyk, 1994; word segmentation: Jusczyk, Hohne, & Baumann, 1999; Mattys & Jusczyk, 2001a), and adjacent phonotactic cues (phonological acquisition: Jusczyk et al., 1993; word segmentation: Mattys & Jusczyk, 2001b; Mattys et al., 1999).

In our case, we showed that the nonadjacent phonological dependencies of their native language that French-learning infants have learned by 10 months of age (Gonzalez-Gomez & Nazzi, 2012; Nazzi, Bertoncini, & Bijeljac-Babic, 2009) are used at the same age to find wordlike units in the speech stream. With respect to the LC bias itself, our findings again revealed effects by 10 months, thus before the ages at which the LC bias has initially been attested in production (Ingram, 1974; MacNeiilage et al., 1999), again supporting a perception- rather than production-based account of this bias (see Gonzalez-Gomez & Nazzi, 2012, for further discussion of this issue).

In the future, studies will have to explore the generality of the present findings for other nonadjacent dependencies. One place to start would be to test the acquisition and use of segmentation of nonadjacent vowel dependencies, given recent evidence showing that consonantal information is more important than vocalic information at the lexical level (Bonatti, Peña, Nespor, & Meehler, 2005; Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet, & Butler, 2009; Nespor, Peña, & Meehler, 2003). In conclusion, the present study provides evidence showing that prior phonotactic knowledge can constrain processes involved in later lexical acquisition, such as the segmentation of word forms from speech stream, even when it involves a nonadjacent dependency.

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References


Appendix

Passages Used in Experiment 1

Condition 1 (/but/–/dip/)

Condition 2 (/pid/–/tub/)

Condition 3 (/bɔd/–/tep/)

Condition 4 (/poet/–/dɔb/)

*Passage also used in Experiment 2.