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PAPER

The development of a phonological illusion: a cross-linguistic study with Japanese and French infants

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Abstract

In adults, native language phonology has strong perceptual effects. Previous work has shown that Japanese speakers, unlike French speakers, break up illegal sequences of consonants with illusory vowels: they report hearing abna as abuna. To study the development of phonological grammar, we compared Japanese and French infants in a discrimination task. In Experiment 1, we observed that 14-month-old Japanese infants, in contrast to French infants, failed to discriminate phonetically varied sets of abna-type and abuna-type stimuli. In Experiment 2, 8-month-old French and Japanese did not differ significantly from each other. In Experiment 3, we found that, like adults, Japanese infants can discriminate abna from abuna when phonetic variability is reduced (single item). These results show that the phonologically induced /u/ illusion is already experienced by Japanese infants at the age of 14 months. Hence, before having acquired many words of their language, they have grasped enough of their native phonological grammar to constrain their perception of speech sound sequences.

Introduction

The adult perceptual system is exquisitely tuned to processing particular sounds of the native language, at the expense of sound patterns that are irrelevant in the language. Such tuning has been linked to the learning processes which take place during the first years of life. Starting around 6 months of age, infants become sensitive to native vowels (Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992; Polka & Werker, 1994); at 12 months, they have become unable to perceive some non-native consonantal contrasts (Werker & Tees, 1984). Importantly, this early perceptual tuning process cannot be based on an analysis of the native language lexicon, whose acquisition has barely begun (Fenson, Dale, Reznick, Bates, Thal & Pethick, 1994); instead it has to rely on an analysis that can be performed on the speech signal itself, a statistical analysis of the phonetic properties of speech sounds (Anderson, Morgan & White, 2003; Maye, Weiss & Aslin, 2008; Maye, Werker & Gerken, 2002; White, Peperkamp, Kirk & Morgan, 2008).

Do all aspects of the native language undergo similar perceptual tuning? Languages differ not only in the inventory of particular segments (consonants and vowels), but also in the phonological grammar which governs how segments can be assembled in a linear sequence. For instance, in languages that allow only a restricted set of syllable types, like Japanese, most consonants (C) are obligatorily followed by a vowel (V). In others with more complex syllabic types, like French or English, one can find long series of consonants (e.g. CCCVCC as in 'strict'). Several studies have shown that adults have trouble perceiving illegal sequences of segments, and even tend to misperceive segments in order to 'repair' these sequences (Hallé, Segui, Frauenfelder & Meunier, 1998). For instance, unlike French adults, Japanese adults perceive a nonword like 'abna' as 'abuna', inserting the illusory (epenthetic) vowel /u/ to break up the illegal consonant cluster (Dupoux, Kakehi, Hirose, Pallier & Mehler, 1999; Dupoux, Pallier, Kakehi & Mehler, 2001; Dehaene-Lambertz, Dupoux & Gout, 2000; Jacquemot, Pallier, Lebihan, Dehaene & Dupoux, 2003). The aim of this paper is to shed light on the mechanisms that may lead to the acquisition of such a phonological illusion in Japanese speakers.

The development of phonologically induced illusions is especially interesting to study. The acquisition of a phonological grammar is potentially much more complex than the acquisition of segmental categories, since it

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implies that infants have to detect and remember sequences of segments and the contexts in which they occur. Indeed, most formal models of phonological acquisition assume that learning takes place through the comparison of underlying lexical representations and surface word forms (Gildea & Jurafsky, 1996; Tesar & Smolensky, 1998, 2000). This presupposes that children have to have acquired a lexicon beforehand, that contains not only word forms but also underlying forms. Supposedly, to recover underlying forms, children would need to have access to at least some morphological alternations, which would imply a rather complex lexical knowledge, potentially including word meanings. This, in turn, predicts that phonological illusions should emerge only after children have acquired a large enough lexicon to enable robust induction of the grammar. In contrast, other models propose that incomplete but robust fragments of the native phonology can be bootstrapped from a bottom-up analysis of distribution of segments (Peperkamp & Dupoux, 2002; Peperkamp, 2003). These models predict that such illusions might appear as soon as infants acquire their native inventories of segments, that is, around 1 year of age.

Experimental studies showing that young infants pay attention to sequential distributional regularities provide supporting evidence for the latter model (e.g. 9-month-olds prefer to listen to words containing legal or frequent sequences of segments, rather than illegal or infrequent ones; Jusczyk, Luce & Charles-Luce, 1994; Jusczyk, Friederici, Wessels, Svenkerud & Jusczyk. 1993, and by 16.5 months of age, they are able to learn phonotactic regularities from a brief exposure; Chambers, Onishi & Fisher, 2003). Yet, showing that infants have become sensitive to the phonotactic regularities of their language is not sufficient to determine whether the phonologically induced illusion is also experienced. Indeed, previous studies on infants' phonotactic acquisition have shown that infants are able to discriminate between the prototypical vs. unusual sequences, since they prefer to listen to prototypical sequences (Jusczyk *et al*., 1993; Jusczyk *et al*., 1994). But it is a quite different phenomenon to 'repair' a non-legal sequence to make it congruent with the native language. Although different languages use different repair strategies (LaCharité & Paradis, 2005), the phonologically induced /u/ illusion in Japanese is a perfect case to study this, since it has been extensively studied in adults (Dupoux *et al*., 1999; Dupoux *et al*., 2001; Dehaene-Lambertz *et al*., 2000; Jacquemot *et al*., 2003).

To study the development of the Japanese phonologically induced /u/ illusion, we tested Japanese and French infants' ability to discriminate between pairs of words such as /abna/ and /abuna/ at 14 months of age. Experimental studies have shown that the phonological /u/ illusion in Japanese only arises at a phonological level of representation, not at an acoustic level. Thus, Japanese speakers have difficulty discriminating between /abna/ and /abuna/, but only when the experimental task includes several talkers and a short-term memory load, thereby preventing participants from focusing on low-level acoustic features (Dupoux *et al*., 1999; Jacquemot *et al*., 2003; see also Dupoux, Peperkamp & Sebastián-Gallés, 2001). When the task involves a less variable set of tokens and less memory load, in contrast, adults find it easy to focus on the presence or absence of the middle vowel, which has strong acoustic correlates (with a duration of 150 ms and high energy, see Table 1). Correspondingly, we tested French and Japanese infants in two tasks: a high-variability task in which infants had to compare many different word pairs (Experiments 1 and 2) and a low-variability task in which they were exposed to a single pair of words (Experiment 3). If Japanese infants have come to experience the phonologically induced illusion, they should fail to discriminate between /abna/ and /abuna/ in the high-variability task but not in the low-variability one. French infants, in contrast, should be able to discriminate between /abna/ and /abuna/ in both cases, since all sequences are legal in French.

Experiment 1

In Experiment 1, we compared the performance of Japanese and French 14-month-olds within a discrimination paradigm that involved maximal phonetic variability. This is an age at which infants have been found to show limited ability to associate the sound and object in a laboratory setting (Stager & Werker, 1997). In addition, their comprehension vocabulary is estimated to contain less than 40 words (Fenson *et al*., 1994). Thus, if Japanese infants at this age already behave as if they perceive illusionary vowels, we can safely conclude that they have not learnt this on the basis of a substantial lexicon.

In this experiment with high phonetic variability, infants were presented with stimuli with a syllabic frame of VCCV or VCuCV, with several different consonants

Table 1 *Acoustic measurements of the stimuli. The durations (in ms) of the first vowel V_1, C_1/C_1u, and the final syllable C_2V_2, and the average F0 were measured. For C_1/C_1u, the durations of closure (or pre-voicing) are shown in parentheses*

	V_1 (in ms)	C_1 or C_1u (closure in ms)	C_2V_2 (in ms)	Mean F0 (in Hz)
Experiments 1 & 2				
$V_1C_1C_2V_2$				
abdo, abna, abze, ebda, ebne, ebzo, obde, obza	216.26	178.72 (117.43)	350.50	261.47
$V_1C_1uC_2V_2$				
abudo, abuna, abuze, ebuda, ebune, ebuzo, obude, obuza	214.01	322.82 (95.29)	294.63	254.32
Experiment 3				
$V_1C_1C_2V_2$				
Abna	207.49	156.55 (104.76)	402.41	223.15
$V_1C_1uC_2V_2$				
Abuna	194.15	317.44 (92.33)	310.48	239.46

and vowels taking the C and V slots. If Japanese infants have acquired the phonological grammar of Japanese, they should experience an illusory vowel /u/ within VCCV stimuli. They would then perceive all stimuli as VCuCV, and should therefore fail to discriminate between VCCV and VCuCV, as Japanese adults do. In contrast, French infants should discriminate between these types of stimuli which vary in number of syllables (2 vs. 3). In other words, if Japanese infants perform significantly worse than French infants in this discrimination task, this will show that they have already started acquiring the phonological grammar of Japanese.

Participants

A total of 48 14-month-old infants, 24 French and 24 Japanese (13 and 14 females, mean age: 434 and 432 days, age range: 13.5–14.5 months) participated in this experiment. All participants were healthy, full-term infants raised in either mainly French-speaking or Japanese-speaking families. French infants were tested in Paris, and Japanese infants in Tokyo. In addition, 13 French and 20 Japanese infants participated but their data were excluded from analysis for the following reasons: cried or were fussy (n = 27), parent intervention (n = 3) and technical error (n = 3).

Stimuli

Eight pairs of nonsense word stimuli as shown in Table 1 were used, one of each pair with the sequence VC_1uC_2V (e.g. /abuna/, V: [a, e, o], C_1: [b], C_2: [d, n, z], V [a, e, o]) and the other without the middle vowel [u] (e.g. /abna/). Two tokens of each item (i.e. 16 tokens for /abuna/-type stimuli and 16 tokens for /abna/-type stimuli) were chosen from recordings made by a female French native speaker (second author) so that the vowels and consonants in the stimuli were good tokens of the category in both languages (e.g. all tokens of [e] were judged as good exemplars of /e/ in both French and Japanese). Two sound files were created for /abuna/-type stimuli. Each file contained eight tokens, one of the two tokens for each nonsense word stimulus. They were sequenced randomly with 2 s SOA. The duration of each sound file was approximately 16 seconds long. Similarly, two sound files for /abna/ type stimuli were created. Thus, four sound files were created overall.

Procedure

The modified visual habituation paradigm method (Stager & Werker, 1997) was used. A visual attention getter appeared before all trials, and the experimenter pressed a key to start the trial when the infant looked at it. In each trial of the habituation phase, one of the two sound files corresponding to one type of stimuli was presented, along with a visual stimulus (red and black checkerboard). During trials, the experimenter depressed a key on the computer keyboard while the infant was looking at the checkerboard and released it when the infant stopped looking. Looking time was computed on-line as the cumulated time the infant spent looking at the checkerboard. All trials (habituation and test) lasted 16 seconds. The test phase began when a pre-set criterion had been reached (when the average looking time for the last four habituation trials was less than 65% of the average looking time for the first four habituation trials) or a maximum of 28 habituation trials had been completed. The test phase consisted of two trials, one 'Same' trial in which the infant was presented with the same type of stimulus as during habituation (one of the two sound files they heard during the habituation), and one 'Switch' trial in which the infant was presented with the other type of stimulus. Habituation stimuli type (VC1*u*C2V or VC1C2V) and test trial order (Same then Switch, or Switch then Same) were counterbalanced between subjects. Thus, half of infants were habituated with VC1*u*C2V-type stimuli, while the other half of the infants were habituated with VC1C2V-type stimuli. During the test trials, half of infants were tested in Same then Switch order, while the other half were tested in Switch then Same order.

The experiment was recorded with a video camera placed under the monitor. The test phase was frame-by-frame coded off-line from the video by a trained coder. If the infants can discriminate between the two types of stimuli, they should exhibit longer looking times for Switch trials than Same trials.

Results

The average looking times for Same and Switch trials for each group are presented in Figure 1. A repeated-measures analysis of variance, with Language (Japanese vs. French) as a between-subjects factor and Trial Type (Same vs. Switch) as a within-subject factor revealed that there was no main effect of Language ($F(1, 46) = .05$, $p = .82$), while the main effect of Trial Type was marginally significant ($F(1, 46) = 3.71$, $p = .06$). The

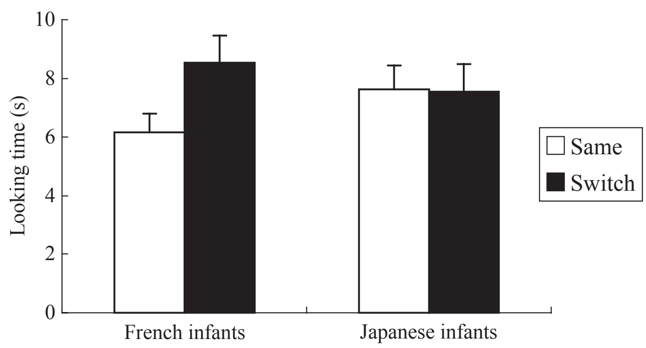

Figure 1 *Average looking times during Same and Switch trials for French and Japanese 14-month-old infants in the high phonetic variability condition. Error bars represent the standard error of the difference between Switch and Same trials.*

interaction between Language and Trial Type was significant ($F(1, 46) = 4.25$, $p = .045$). Planned contrasts of the means for each language showed that French infants had significantly longer listening times to Switch than Same trials ($F(1, 46) = 7.95$, $p = .007$), while Japanese infants showed no difference ($F(1, 46) = .01$, $p = .92$).

This experiment thus uncovered a significant cross-linguistic difference between Japanese and French infants at 14 months: French infants discriminated between *abna* and *abuna*, while Japanese infants did not. In this condition where many different words exemplifying the basic pattern were used, French infants must have noticed the difference between the two types of stimuli by encoding the habituation stimuli as consisting of either two syllables (if they got habituated with *abna*-type stimuli), or three syllables (if they got habituated with *abuna*-type stimuli). For Japanese 14-month-olds, in contrast, this same difference did not seem to be noticeable. This pattern of results is consistent with our prediction and suggests that it is likely that they perceive an epenthetic vowel, and hear *abna* as *abuna*, like adult Japanese speakers in Dupoux *et al*. (1999). Since 14-month-olds still have a very limited lexicon, this result shows that the part of Japanese phonological grammar that gives rise to the perceptual illusion is acquired before infants have amassed a large vocabulary. Infants do not rely on a full-fledged analysis of their native language lexicon to learn this regularity of their language.

Before we can confidently draw this conclusion, we need to demonstrate that Japanese infants are able to process the kind of stimuli that were used in the present experiment. We will do this in Experiment 3, that relies on a design with low phonetic variability. Before we move on to this, however, we wanted to see whether even younger infants might already have learnt this phonological regularity of Japanese. To this end, we tested 8-month-old Japanese and French infants with the exact same experimental design in Experiment 2.

Experiment 2

Participants

A total of 48 8-month-old infants, 24 French and 24 Japanese infants (10 and 9 female, mean age: 252 and 246 days, age range: 7.5–8.5 months) participated in this experiment. All participants were healthy, full-term infants raised in either mainly French-speaking or Japanese-speaking families. French infants were tested in Paris, and Japanese infants in Tokyo. Nine French infants and 11 Japanese infants were excluded from analysis for crying or fussiness.

Stimuli and procedure

The stimuli and procedure were the same as in Experiment 1.

Results

The average looking times for Same and Switch trials for Experiment 2 are presented in Figure 2. A repeated-measures analysis of variance, with Language (Japanese vs. French) as a between-subjects factor and Trial Type (Same vs. Switch) as a within-subject factor revealed a significant main effect of Language ($F(1, 46) = 5.29$, $p = .026$), showing that Japanese infants overall listened to the stimuli longer than French infants. The main effect of Trial Type was also significant ($F(1, 46) = 5.26$, $p = .027$), showing that, overall, infants listened to Switch trials longer than to Same trials. No significant interaction between Language and Trial Type was found ($F(1, 46) < 1$, $p > .45$), showing that the two populations did not behave significantly differently with regard to the task.

The lack of a significant interaction between Language and Trial Type suggests that both populations behaved similarly, although numerically there was a trend for greater discrimination in French than Japanese infants. The significant main effect of Trial Type shows that, overall, infants discriminated between the two types of stimuli (longer listening times for Switch than for Same trials). This is consistent with studies showing that newborn infants are able to discriminate between bi- vs. tri-syllabic stimuli (Bijeljac-Babic, Bertoncini & Mehler, 1993). Since there is no significant cross-linguistic difference, we can conclude that at the age of 8 months, Japanese infants have not yet fully acquired the fragment of the phonological grammar that leads to the perception of the illusory /u/ vowel. In contrast, 14-month-olds' behavior shows that they have already acquired this characteristic of Japanese phonology. Therefore, this acquisition takes place at some point between the ages of 8 and 14 months.

Experiment 3

In Experiment 3, we tested Japanese infants in a discrimination task with low phonetic variability: the VCCV and VCuCV categories were exemplified by one word

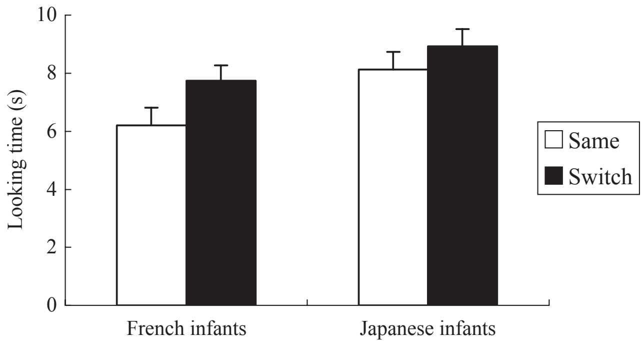

Figure 2 *Average looking times during Same and Switch trials for French and Japanese 8-month-old infants in the high phonetic variability condition. Error bars represent the standard error of the difference between Switch and Same trials.*

each, 'abna' vs. 'abuna'. Since this task allows infants to focus on the acoustic differences between stimuli, and does not require an abstract phonological representation, we predict that Japanese infants should be able to discriminate between them, just like Japanese adults would do in similar circumstances. Such a positive result would show that Japanese infants are able to perceive the acoustic features that distinguish between the two types of stimuli. Indeed, as can be seen in Table 1, the two types of stimuli differ by more than 100 ms in vowel duration, a difference that should be noticeable, since other studies have reported that Japanese infants are capable of discriminating vowel duration differences of this size (Sato, Sogabe & Mazuka, 2010; Mugitani, Pons, Werker & Amano, 2009). In addition, if Japanese 14-month-olds are able to discriminate between 'abna' and 'abuna' in the low-variability task, this will also ensure that their failure to discriminate in Experiment 1 was not due to some inherent difficulty with the experimental task or the stimuli (which were produced by a French speaker).

Participants

Twenty-four 8-month-old and 24 14-month-old Japanese infants participated in this experiment (13 and 13 females, mean age: 249 and 424 days, age range: 7.5–8.5 and 13.5–14.5 months for the 8- and 14-month-olds, respectively). All participants were healthy, full-term infants raised in Japanese-speaking families and tested in Tokyo. In addition, the results from five 8-month-olds and 14 14-month-olds were excluded from analysis for crying or fussiness (17), falling asleep (one) or experimenter error (one).

Stimuli

One pair of nonsense word stimuli *abna/abuna* was randomly selected from the stimuli used in Experiments 1 and 2. Eight tokens of each item were chosen from recordings made by the same female French native speaker. They were selected so that the vowels and consonants in the stimuli were good exemplars of the category in both French and Japanese. The acoustic measurements of the stimuli are summarized in Table 1.

Procedure

The procedure was the same as in Experiment 1.

Results

A repeated-measures analysis of variance, with Age (8 vs. 14 months) as a between-subjects factor and Trial Type (Same vs. Switch) as a within-subject factor, revealed a main effect of Trial Type ($F(1, 46) = 7.39$, $p = .009$), showing that Japanese infants listened longer to Switch than Same trials. It also revealed a main effect of Age

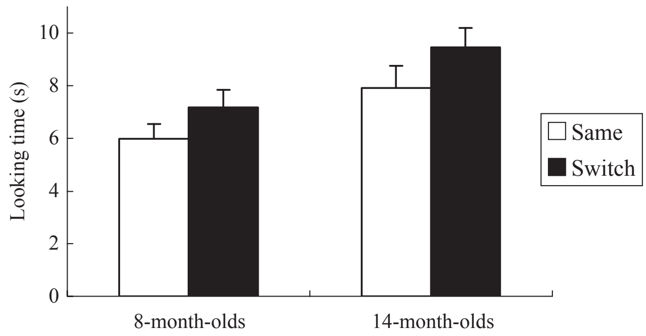

Figure 3 *Average looking times during Same and Switch trials for Japanese 8- and 14-month-old infants in the low phonetic variability condition. Error bars represent the standard error of the difference between Switch and Same trials.*

($F(1, 46) = 5.48$, $p = .024$), showing that 14-month-olds had longer listening time overall. The interaction between Age and Trial Type was not significant ($F(1, 46) = .12$, $p > .10$). As shown in Figure 3, the results showed that Japanese infants discriminated *abna* from *abuna* in the absence of phonetic variability.

This positive discrimination result thus shows that Japanese infants are able to discriminate stimuli based on the presence/absence of a middle vowel (as expected from the literature; Sato *et al.*, 2010; Mugitani *et al.*, 2009). It is also consistent with the results of Kajikawa, Fais, Mugitani, Werker and Amano (2006), showing that Japanese 6-, 12- and 18-month-olds can discriminate between /neeks/ and /neekusu/ in a low phonetic variability discrimination paradigm. In addition, this positive result ensures that Japanese 14-month-olds are willing to perform the visual habituation task, and do not experience any special difficulty with the stimuli themselves (even though they were uttered by a French speaker). As a result, their failure in the high-variability task of Experiment 1 reflects a bona fide difficulty to discriminate between /abna/ and /abuna/ in the presence of high phonetic variability.

Discussion

In this paper, we documented a cross-linguistic difference in the discrimination between VCCV and VCuCV stimuli by French and Japanese 14-month-old infants. In Experiment 1, 14-month-old French infants showed a robust ability to discriminate between VCCV and VCuCV in a high-variability context, while Japanese infants at the same age showed no significant discrimination. Experiment 2 showed that at 8 months, Japanese infants did not differ significantly from French infants.

The performance of Japanese infants is most consistent with the account that the phonologically induced /u/ illusion (perceptual epenthesis) is already in place by the age of 14 months. First, the fact that Japanese infants were able to discriminate /abuna/ versus /abna/ in the absence of high phonetic variability (Experiment 3) rules out the possibility that the failure of 14-month-olds in the high phonetic variability condition was the result of their inability to exploit the acoustic cues that distinguish the two types of stimuli, or to perform the experimental task in the presence of illegal stimuli.

Second, managing to learn the prototypical phonotactic patterns of one's mother tongue *on its own* does not explain the failure to discriminate the illegal clusters from prototypical sequences. Previous studies on the acquisition of phonotactic knowledge in infants relied on the head-turn preference paradigm and found that by 9 months, English-learning infants show a preference for the phonotactic patterns that are legal or more frequent in their language over illegal or less frequent ones (Jusczyk *et al.*, 1993; Jusczyk *et al.*, 1994). These studies demonstrate that infants are able to discriminate the legal (or more frequent) sequences from illegal (or less frequent) sequences, even though they have already learned which ones are more prototypical in their language. The results of the present study thus go beyond the mere sensitization to language-specific phonotactic patterns.

Instead, our results can be most straightforwardly accounted for if we assume that Japanese infants have come to experience the phonologically induced /u/ illusion by 14 months of age. Japanese adults insert an epenthetic vowel /u/ when they attempt to produce foreign words that contain consonant clusters that are illegal in Japanese. When they hear /abna/, they report 'hearing' an illusory vowel /u/, and as a result, they find it difficult to discriminate /abna/ from /abuna/. French adults, in contrast, easily produce /abna/ and /abuna/ distinctively, they do not 'hear' /u/ in /abna/, nor do they have difficulty discriminating the pair (Dupoux *et al.*, 1999). While the Japanese and French infants did not differ significantly from each other at 8 months, they behaved significantly differently at 14 months. French 14-month-olds, like French adults, showed no difficulty discriminating the pair, while Japanese 14-month-olds, like Japanese adults, were unable to discriminate the pair.

In sum, we found that the acquisition of perceptual epenthesis takes place by 14 months of age which is on a par with that of segmental categories (Werker & Tees, 1984; Polka & Werker, 1994; Kuhl *et al.*, 1992; Stager & Werker, 1997) and of the statistical regularities of segment sequences (Chambers *et al.*, 2003; Kajikawa *et al.*, 2006; Jusczyk *et al.*, 1993; Jusczyk *et al.*, 1994). The acquisition presumably take place primarily using the statistical learning mechanisms which only refer to distributions of sounds within utterances, before the information from a large lexicon becomes available (Maye *et al.*, 2002; Chambers *et al.*, 2003; Peperkamp, Le Calvez, Nadal & Dupoux, 2006; Anderson *et al.*, 2003; White *et al.*, 2008). Still, vowel epenthesis has traditionally been analyzed as an integral part of phonological grammar (Rose & Demuth, 2006; Uffmann, 2006). Indeed, the repair of illegal syllabic structures is not universal but depends on language-specific properties: depending on the language, repairs are done through deletions, epenthesis or segmental change (LaCharité & Paradis, 2005). But if epenthesis depends on acquisition of the full phonological system, it should be observed only after the acquisition of a sufficient number of words (Gildea & Jurafsky, 1996; Tesar & Smolensky, 1998, 2000). The fact that it arises by 14 months makes this claim unlikely and reinforces the view that infants first undergo a statistical learning phase, where incomplete but robust fragments of the phonological grammar are inferred on the basis of a distributional bottom-up analysis of continuous speech, which may or may not be segmented into word-sized units (Peperkamp & Dupoux, 2002; Peperkamp, 2003; Peperkamp *et al.*, 2006). Such an early acquisition would provide the foundations for a more complete lexical-based learning (Pierrehumbert, 2003). It would also result in long-lasting perceptual tuning and thereby explain the difficulties adults have in perceiving foreign languages.

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