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Learning classes of sounds in infancy

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1 Introduction

Infants' speech perception has been shown to change from an acoustic-based sensitivity to a language-specific one over the first year of life (Jusczyk 1997), such that around the end of that year, infants exhibit some knowledge of their ambient language's phonological system, including its sounds (Werker and Tees 1984), its stress pattern (Jusczyk, Cutler, and Redanz 1993), and the constraints on the position and co-occurrence of sounds, that is, phonotactics (Jusczyk, Friederici, Wessels, Svenkerud, and Jusczyk 1993). In the present paper, we explore infants' sensitivity to phonotactics in an artificial grammar, in order to gain an insight into the mechanisms that allow infants to learn phonotactics in their ambient language. Specifically, we assess the possibility that infants' learning comes to be affected by perceptual biases acquired as they accumulate experience with language.

Recent experimental work underlines the potential importance for language acquisition of statistical learning mechanisms, which are based on tracking frequency distributions. Although most often associated with word segmentation (e.g., Saffran, Aslin, and Newport 1996), it has been suggested that statistical learning may account for many other aspects of language development, from hierarchical structure (Gomez & Gerken 1999) to the phonological inventory (Maye, Weiss, and Aslin 2008; Maye, Werker, and Gerken 2002), and it is conceivable that it could also contribute to phonotactic acquisition. Indeed, if infants can parse the speech stream into something like segment-sized or syllable-sized elements, they would then be able to track co-occurrences among those units, and between those units and phonological breaks (such as word boundaries). However, it is unlikely that infants are blindly tracking all possible statistics in the speech they hear, as even the simplest speech samples can be described at multiple levels and the statistics to be computed quickly multiply beyond reasonable infant processing and memory abilities. For instance, imagine a sound system with 20 sounds and 2 positions, such that possible syllable/words are of the shape #XX#. This imaginary system is much simpler than what occurs in natural languages; yet even in this simplified environment, considering all conceivable sound patterns would involve keeping track of 20^3 statistics.

One may propose that the task is simplified if learners do not keep track of combinations that are not evidenced; thus, all combinations with frequency zero are considered impossible and phonotactic frequency effects would operate only among strings that are present in the input. However, this would limit learners' generalization abilities in ways that are inconsistent with most findings in infant and adult pattern learning (Cristià and Seidl 2008, Finley and Badecker 2009, and Wilson 2006; see also Peperkamp and Dupoux 2007, Peperkamp, Skoruppa, and Dupoux 2006). For instance, Finley and Badecker (2009) demonstrated that adults can learn a vowel harmony rule (vowels in consecutive syllables are similar to one another) and generalize it to vowels that were not part of the training set. Although these generalization vowels had a frequency of zero during training, adults nonetheless extended the familiarized pattern to novel vowel combinations, instead of treating them as illegal, as would be expected by their co-occurrence frequency during initial exposure.

There is an alternative explanation that could account for *both* the rapidity in learning *and* the ability to generalize. This explanation relies on the hypothesis that phonotactic pattern learning is guided by perceptual and memory constraints which direct learners' attention to specific aspects of the input. Although referring to word segmentation, Aslin and Newport (2009:16) propose that perceptual biases could "constrain [statistical learning] to enable rapid learning to be tractable given the limits of human information processing and the explosive combinatorics of even the simplest language." The adult phonotactic learning literature documents several possible candidates for such perceptual biases. For example, tracking phonotactics at word-edges is easier than at word-middles (Endress and Mehler 2010); vowel-vowel and consonant-consonant dependencies are easier than vowel-consonant co-occurrences (Moreton 2008); and a constraint on a set of sounds sharing phonetic characteristics, a natural class, is easier than one on an arbitrary set of sounds (Kuo 2009). At this point, however, it becomes pressing to investigate the etiology of these perceptual biases. For example, while it is intuitive that word-edges would be more salient than word-middles, it is not equally clear how a learner may determine which sounds form a natural class. Without this knowledge, the usefulness of the perceptual bias is greatly reduced; indeed, how may the infant focus first on natural classes unless she knows which they are?

One possibility is that infants can determine which sounds form a natural class because they have innate access to phonological features. For example, Cristià and Seidl (2008) report that 7-month-olds exposed to a constraint involving both nasal and stop consonants learned the pattern and generalized it to untrained stop consonants, but failed to generalize when exposed to a constraint on nasal and fricative consonants. One interpretation of this result is that learning is constrained by abstract phonological features that are a part of Universal Grammar (Chomsky and Halle 1968, Donegan and Stampe 1979). In this case, upon hearing nasal and oral stop consonants in word-initial position, infants would be able to represent this regularity as "#[-continuant]", a pattern that is simpler than the conjunction of features needed to identify nasals and fricatives as a class.

Nonetheless, those results could equally well be accommodated by a theory where natural classes emerge as a side effect of phonetic experience. For instance, normally-developing 7-month-olds have begun to babble some nasal and oral stop consonants (but few fricatives; Gildersleeve-Neumann, Davis, and MacNeilage 2000). Nasal and oral stops share a buccal gesture and differ only in the position of the velum; that is, the mouth configuration is exactly the same for nasal and oral stops for each place of articulation, whereas for fricatives the closure gesture cannot be complete, in order to allow the passage of air to produce frication. In view of this articulatory similarity and infants' experience babbling nasal and oral stops, it is reasonable that the natural class advantage has arisen from experience, rather than being given by Universal Grammar.

If our hypothesis, that this particular perceptual bias favoring natural classes emerges over the course of development, is correct, then we would expect younger infants to be able to learn and generalize sound patterns affecting the more dissimilar grouping of nasals and fricatives. To explore this hypothesis, we tested a group of 4-month-old infants with the same materials and procedure as the 7-month-olds tested in Cristià and Seidl (2008). This younger age group was chosen because it is the youngest age at which the same procedure can be used.

2 Experiment

In this experiment, we explored 4-month-olds' ability to learn two abstract sound classes. Infants were exposed to non-words instantiating a phonotactic constraint on a group of sounds: for half of the infants, the group of sounds formed a phonetic class (nasals and stops; the S&N condition); for the other half, it was an arbitrary grouping (nasals and fricatives; the F&N condition) group. During test, infants' preference for novel non-words with legal versus illegal onsets was gauged. Crucially, the onsets presented during test had not been instantiated in onset position during familiarization. Therefore, in order to succeed at the task, infants needed not only to learn the specific phonotactic regularities presented in familiarization, but also to represent them in terms abstract enough to encompass the untrained onsets presented in test. If the perceptual bias favoring the S&N class is a result of experience rather than an innate predisposition, we predicted that 4-month-olds would succeed in both S&N and F&N condition, which would be reflected statistically as a main effect of Legality (legal versus illegal onset) and no significant interaction with Condition (S&N, F&N).

2.1 Methods

The experiment consisted of two phases, familiarization and test. During familiarization, infants heard non-words whose onsets belonged to a specific class (e.g., /t,g,m,n/). At test, infants heard non-words with novel onsets. In half the trials, the onset belonged in the same class as in the familiarization (legal, e.g., /b,k/), and in the other half the onsets did not belong to the familiar group of sounds (illegal, e.g., /v,ʃ/). Infants' attention was measured in each type of trial. Since all test onsets were equally novel, infants had to generalize in order to succeed. Success is indicated by significantly longer looking times to one type (typically to illegal trials).

2.2 Participants

Forty-eight 4-month-olds (M = 4.25, range 3.98-4.57, 22 female) full-term monolingual English-learning infants were tested. A further 13 infants did not complete the testing for fussing or crying (12), or equipment error (1). It should be noted that results with only 24 infants show the same pattern of results. (The number of participants was this high, compared to the 24 included in Cristià and Seidl 2008, in order to rule out that the lack of a significant interaction with condition was simply due to lack of statistical power.)

2.3 Stimuli and design

The stimuli and design were exactly the same as in Cristià and Seidl (2008). Infants heard C_1VC_2 non-words, where V could be one of /i, a, ɔ, u/ and C_2 any permissible coda in English (/m, n, ŋ, l, r, f, v, s, z, ʃ, dʒ, tʃ, p, b, t, d, k, g/). Consonants in C_1 could be nasals and stops for half the infants (the S&N condition); or nasals and fricatives, for the other half (the F&N condition). In order to ensure that results were not driven by the particular sounds used, half of the participants in each condition (e.g., S&N) were familiarized with certain obstruents (/b,k/) and tested with others (/t,g/), and vice versa (familiarized with /t,g/, tested with /b,k/). This design is summarized in Table 1, and the full list of non-words may be found in Cristià and Seidl (2008).

	Familiarization		Testing
	Stops and Nasals	Fricatives and Nasals	
Order A	t, g, m, n	f, z, m, n	v, ʃ, b, k
Order B	b, k, m, n	v, ʃ, m, n	f, z, t, g

Table 1: Summary of the design: Infants heard 57 different non-words, where the possible onsets were determined by the familiarization condition and order. For example, infants in the Stops and Nasals condition, Order A, heard words beginning with /t, g, m, n/, while infants in the Fricatives and Nasals condition of the same order heard /f, z, m, n/ as possible onsets. Both groups were subsequently tested with non-words beginning in /v, ʃ/ (illegal onsets for the Nasals and Stops group, but legal onsets for the Nasals and Fricatives condition) and /b, k/ (illegal for the Nasals and Fricatives infants, but legal in the Nasals and Stops condition).

Sixty non-words for each condition were generated randomly; 57 were presented during familiarization (for a total of 100 s) and 3 were reserved for testing (for a total of 5.5 s, repeated a maximum of 3 times per trial). Non-words had similar rhymes across sets. When in the S&N condition a given word began with a stop (e.g., /b/), the corresponding word in the F&N condition began with a fricative (e.g., /v/). The sequences were produced by a female American English speaker in an infant-directed register using a list intonation.

2.4 Apparatus and Procedure

The apparatus and procedure were identical to Cristià and Seidl (2008), an adaptation of the Head-Turn Preference procedure (Jusczyk and Aslin 1995) used in previous phonotactic learning studies in infancy (e.g., Chambers, Onishi, and Fisher 2003). The infant sat on a caregiver's lap in the center of a three-sided booth, with a green light in front of the infant, and red lights on each side. The equipment and the experimenter, who observed the infant's headturns through a peephole, were concealed from the infant's view. The experimenter and the caregiver wore tight-fitting Peltor Aviation headphones through which they listened to loud masking music in order to blind them from the stimuli the infant was hearing. All choices of presentation were made randomly by a computer program.

Every trial started with the light at the front flashing, which was extinguished when the infant oriented forward. Then, one of the side-lights began flashing. Once the infant oriented to the side-light, the auditory stimuli would be played for as long as the infant maintained that orientation. If the infant turned away for more than 2 s, this side-light was extinguished and the light at the front began flashing again. During the familiarization phase, the sound file was presented until its completion, irrespective of the infant's behavior, and only the lights were contingent on the infant looking. During testing, both light and sound were contingent on the infant looking, and the test file was looped until the infant made a criterion look-away, or a maximum of 3 repetitions were reached.

2.5 Results

A repeated-measures ANOVA with Looking Times as dependent variable, Legality (Legal, Illegal) as repeated measure, and Condition (S&N, F&N) and Sound Sample (A, B) as factors suggests that the only effect was that of Legality, which is highly significant [$F(1,44) = 11.56$, $p = .001$, all other Fs < 1, except for Order*Condition: $F(1,44) = 3.01$, $p = .09$]. This effect of Legality on Looking Times arose because most infants looked reliably longer during illegal trials (in the S&N condition, 15/24 infants displayed this trend, and the looking times were significantly different in a paired two-tailed t-test: $t(23) = 2.03$, $p = .05$; in the F&N, 18/24, $t(23) = 2.82$, $p = .009$). Average looking times to illegal and legal trials in the two age groups tested with this method are plotted in Figure 1.

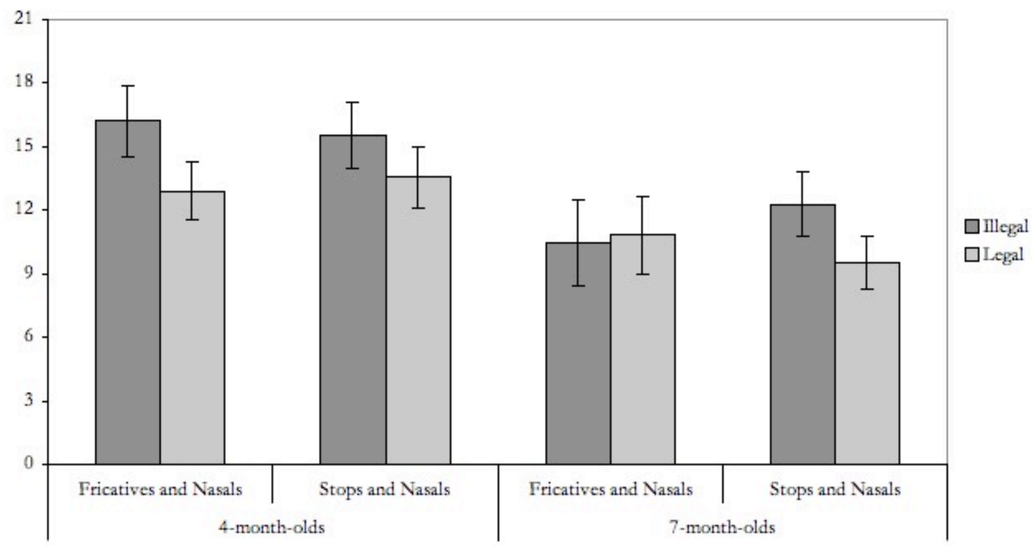

Figure 1. Average looking times by Condition and Legality in the 4- and 7-month-olds' groups (error bars represent standard error).

These results suggest that 4-month-olds, unlike the 7-month-olds in Cristià and Seidl (2008), were able to generalize in both conditions. To confirm that the pattern of results was dissimilar in the two age groups here and those in Cristià and Seidl (2008), a repeated-measures ANOVA incorporating Age Group as an additional variable was carried out. In effect, there was a three-way interaction of Age Group*Condition*Legality [$F(1,64) = 5.55$, $p = .02$, due to the fact that the 4-month-olds' listening preferences were not impacted by condition, but the 7-month-olds' were. There were also main effects of Age Group: $F(1,64) = 6.86$, $p = .01$, due to the reliably longer looking times in the younger age group; and Legality: $F(1,64) = 9.17$, $p = .004$, due to overall longer looking to illegal forms; and a marginal interaction Age Group * Legality: $F(1,64) = 3.13$, $p = .08$, due to the fact that 4-month-olds showed a stronger preference for illegal forms than the 7-month-olds].

An alternative explanation may be put forward: In these stimuli, the restricted segments (both fricatives and stops) could also appear in word-final position; by chance, in the random generation of stimuli, fricative occurred somewhat more frequently in codas than stops did, thus rendering the F&N pattern more gradient than the S&N one (although they would both be gradient). Therefore, if the 7-month-olds were attending to the codas, while 4-month-olds were not, then the presence of obstruents in both onset and coda could confuse them, particularly in the F&N condition. This explanation is unlikely, as it relies on three assumptions, none of which has been demonstrated for infants (of either age). First, in order to be thus confused, infants should be keeping track of both syllable-initial and syllable-final position. However, there is a good deal of experimental evidence showing that even older infants do not attend to word-final phonotactics, as demonstrated by preference studies (e.g., 9-month-olds detect similarities across word onsets, but not codas in Jusczyk et al. 1999), and phonotactic sensitivity ones (compare 9 months for word-initial phonotactics with 16 months for word-final phonotactics; Zamuner 2006). The second assumption is that 7-month-olds should have integrated fricatives and stops across positions into a single representation. Although there is no experimental research addressing this question, context-independent representations remain controversial at the phonetic level (see, e.g., Pierrehumbert 2003). The final piece of this argument is to assume a degradation of performance that is directly proportional to gradiency. While it is true that adults are affected by the relative strength of constraints (Goldrick 2004, Lee and Goldrick 2008), there is absolutely no evidence of it in infancy. Furthermore, this explanation would be incompatible with the results of Cristia and Seidl's Experiment 2, where 7-month-olds with the *same* stimuli minus nasal-initial tokens. Through this manipulation, both conditions now involved natural classes, but the imbalance in fricative vs. stop codas was not removed. Yet, infants in both conditions learned, suggesting that the key element in their performance was the naturalness of the class rather than a difference in the degree of gradiency. In short, we can safely conclude that the difference in learning abilities had more to do with the sounds appearing in the onset than with those in the coda, and how the onsets may have been integrated into more general classes, as further discussed in the next section.

3 Discussion

Learning phonotactics is not a straightforward task: it is necessary to both chunk the input into units (be it syllable- or segment-sized), and compute the frequency of occurrence of these units with respect to phonological boundaries and to each other. Computing these frequencies could become a daunting task, as most sound inventories contain at least a couple dozen sounds, exceeding the memory of a learner who tries to keep track of all possible combinations. However, evidence from adult learning suggests that the pattern-finding process is guided by perception and memory, such that learners do not compute all probabilities at once, but rather they are guided by biases that make certain patterns more salient than others. Naturally, proposing that statistical learning is constrained by perceptual biases only moves the weight of the explanation to the biases themselves. For some documented tendencies, this move does not presuppose loading the learner with language-specific knowledge. For example, the delay between sensitivity to onset (at 9 months: Juszcyk, Luce, and Charles-Luce 1994, Jusczyk, Friederici, Wessels, Svenkerud, and Jusczyk 1993) and coda (17 months: Zamuner 2006) phonotactics may be interpreted as suggestive of a a general processing bias favoring attention to beginnings; or to a perceptual advantage due to the clearer articulation of onsets as compared to codas (e.g., Byrd 1996). In contrast, the origins of other documented tendencies are more mysterious. For instance, Saffran and Thiessen (2003) showed that a phonotactic constraint based on an arbitrary set of sounds did not allow subsequent word segmentation by 8-month-olds, whereas a constraint based on a natural class did. This could have been due to the natural class bias operating on the computation of phonotactics, and then cascading into word segmentation (Brent and Cartwright 1996, Mattys and Jusczyk 2001). It is undeniable that such a tendency could simplify the learning task for the infant by reducing the number of patterns that are computed. In the present experiment, for example, instead of learning four specific patterns (e.g., "#b", "#k", "#m", "#n"), infants could learn a single pattern describing all four instantiations (e.g., "[-continuant]"). But are infants innately driven to treat certain sounds as a class, or do they come to learn which sounds form a natural class, and which do not, through language exposure?

Our results suggest that this bias emerges between 4 and 7 months of age. The fact that it emerges over the course of development, as infants accrue productive and perceptual experience, may be interpreted as supporting the hypothesis that experience itself can constrain learning, rather than being innately specified. This proposal resonates with current work in phonological theory, where natural classes are emergent rather than innate (Mielke 2008) and where abstract phonological knowledge may be induced from phonetic experience (Hayes and Steriade 2004).

It is conceivable that infants can also develop biases regarding the phonetic groundedness of a pattern, similarly to the way adults find it easier to learn sound alternations that are grounded on phonetics. For example, all else being equal, alternations are easier to learn if the phonetic change between underlying and surface form is minimal (e.g., "g" turning into "k" is easier than "g" turning into "p": Skoruppa, Lambrechts, and Peperkamp, to appear; see also Peperkamp, Skoruppa, and Dupoux 2006, Schane, Tranel, and Lane 1974), and the existence of phonetic bases for an alternation may influence generalization abilities (e.g., being trained on palatalizing velars before mid vowels makes transferring this change to high vowels easier, but not vice versa; Wilson 2006). While it seems clear that adults' learning of alternations is influenced by phonetic groundedness biases, the evidence in favor of phonetically grounded, static patterns is scarce. Segmental harmony (for example, when vowels in neighboring syllables share acoustic features) has been investigated in both infant and adult populations providing no clear evidence in favor of phonetic groundedness, as they can learn equally well both harmonic (more natural and frequent) and disharmonic patterns (Pycha, Nowak, Shin, and Shosted 2003, Seidl and Buckley 2005). Similarly, Moreton (2008) reports no difference in adults' laboratory learning of a phonetically grounded vowel-vowel constraint, and that of a consonant-consonant constraint with virtually no phonetic precursors. Nonetheless, it can be argued that these results could be simply due to a ceiling effect, and more research on this topic would be welcome, since the emergence of groundedness effects has begun to be documented on other phonological domains (e.g., in stress pattern learning; Gerken and Bollt 2008).

Throughout this article, we have referred to these principles that may restrict infants' phonotactic learning as biases, rather than constraints. This is because they probably only guide infants' attention, rather than altogether preventing learning of patterns that do not comply with them. Unnatural and ungrounded patterns are learned over the course of acquisition (Buckley 2000), and in laboratory learning after brief exposures. For example, English-hearing toddlers (16.5-month-olds; Chambers et al. 2003) and adults (e.g., Onishi, Chambers, and Fisher 2001) quickly acquired novel phonotactic patterns that do not follow any of the biases discussed here. In those studies, participants heard non-words that could begin with /b, k, m, t, f/ and end with /p, g, n, tʃ, s/, or vice versa and were able to learn these patterns despite the lack of internal coherence of the sounds assigned to each position, and despite the fact that nothing in those sets seemed to respond to the phonological environment; for example, there is no articulatory or perceptual reason why /b, k, m, t, f/ should happen word-initially.

To conclude, results of the present study suggest a developmental change in infants' ability to learn and generalize phonotactic constraints, providing a key piece of evidence concerning the question of how and when infants combine statistical learning and phonological knowledge in language acquisition. Phonotactic learning is a powerful mechanism that allows infants (and other human and non-human learners) to encode co-occurrences. However, its weakness as an explanatory mechanism is betrayed by that same power, and it has become increasingly important to document the ways in which it is guided. We hypothesized that, just as perceptual and phonological knowledge can trump purely statistical segmentation strategies (e.g., Johnson and Jusczyk 2001), it might also guide phonotactic learning. Indeed, experimental results from both infants and adults have begun to suggest some perceptual biases that may guide phonotactic learning. For instance, Cristià and Seidl (2008) identified this natural class bias affecting infants' generalization skills within the domain of phonotactics itself. Our results further demonstrate that infants' ability to generalize patterns to untrained, similar sounds becomes increasingly constrained with age and experience, such that the bias towards natural, phonetic classes may emerge as a function of increased experience. Thus, this study contributes to documenting the emergence of biases that shape infants' learning of phonotactics, thus ameliorating the exponential complexity of a purely statistical learning account.

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