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Distributional Phonetic Learning at 10 Months of Age

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Infant phonetic perception reorganizes in accordance with the native language by 10 months of age. One mechanism that may underlie this perceptual change is distributional learning, a statistical analysis of the distributional frequency of speech sounds. Previous distributional learning studies have tested infants of 6–8 months, an age at which native phonetic categories have not yet developed. Here, three experiments test infants of 10 months to help illuminate perceptual ability following perceptual reorganization. English-learning infants did not change discrimination in response to nonnative speech sound distributions from either a voicing distinction (Experiment 1) or a place-of-articulation distinction (Experiment 2). In Experiment 3, familiarization to the place-

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of-articulation distinction was doubled to increase the amount of exposure, and in this case infants began discriminating the sounds. These results extend the processes of distributional learning to a new phonetic contrast, and reveal that at 10 months of age, distributional phonetic learning remains effective, but is more difficult than before perceptual reorganization.

Language learning is a complex, multilayered process that is accomplished by human infants with apparent effortlessness, no matter to which language(s) they are exposed. A crucial element of linguistic competence, lexical interpretation, rests on native speech perception. English speakers must discriminate between the words *rake* and *lake*, and Japanese speakers must disregard the same (but for them, meaningless) difference. Phonetic perception facilitates native speech sound contrasts and collapses nonnative ones (Jusczyk, 1993; Kuhl, 1993; Werker & Desjardins, 1995). Infants begin life with broad-based phonetic sensitivity, with native language phonetic structure developing by 10 months of age (Anderson, Morgan, & White, 2003; Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995; Kuhl et al., 2006; Narayan, Werker, & Beddor, in press; Werker & Tees, 1984).

Infants' phonetic development has a number of available guiding resources. Some information may be gleaned from nonauditory sources. For example, 6-month-old infants show an influence of visual speech information, ceasing discrimination of native sound distinctions produced with the same facial configuration (Teinonen, Aslin, Alku, & Csibra, 2008), and 9-month-old infants show an influence of top-down visual information, enhancing discrimination of sounds that co-occur with distinct objects (Yeung & Werker, 2009). A complementary approach exploits the frequency distributions of speech sounds (Werker et al., 2007): Speech sound categories are described by unimodal frequency distributions (most tokens at the category center). Thus, two categories are described by bimodal frequency distributions (with few tokens falling in the boundary between the two). Infants are sensitive to these characteristics (Maye, Werker, & Gerken, 2002). Six- and 8-month-old English-learning infants were exposed to either a bimodal or unimodal distribution of unaspirated alveolar stops from along a voicing continuum that is discriminated as shown in Figure 1 (with some difficulty, although significantly less difficult than at 10–12 months; Pegg & Werker, 1997). Only infants exposed to the bimodal distribution continued to discriminate the contrast; exposure to the unimodal distribution collapsed discrimination (Maye et al., 2002). In another experiment, 8-month-old infants were exposed to a voicing contrast of prevoiced versus short-lag stops that is poorly discriminated at this age, and again only infants exposed to the bimodal distribution later discriminated the contrast—in this case, the

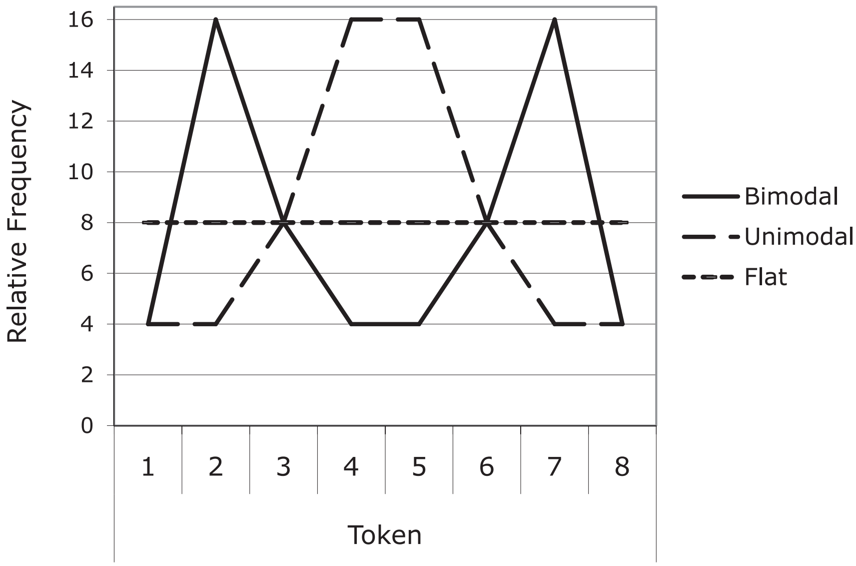

Figure 1. Bimodal, unimodal, and flat distributions of stimuli. Experiment 1 compares bimodal with unimodal familiarizations; Experiments 2 and 3 compares bimodal with flat familiarizations. The *x*-axis denotes the continuum of speech sounds, with Tokens 1 and 8 corresponding to the endpoint stimuli. The *y*-axis shows the relative frequency with which each stimulus is presented.

bimodal distribution had facilitated discrimination (Maye, Weiss, & Aslin, 2008).

At 6–8 months, infants' perception is malleable as they have not yet attuned to the native language. Less is known about infants' distributional learning ability after 10 months of age, following perceptual reorganization. Several factors predict that distributional learning might become more difficult. A statistical line of reasoning suggests that the greater amount of native language information accumulated by 10 months would be more difficult to overcome, especially in a short training period. Further, the emergence of native phonetic categories by this age might result in greater perceptual rigidity given that nonnative distinctions would now be more difficult to perceive (Best, 1995) and would require learning of a second phonetic structure (Flege, 1995). Finally, the perceptual system would have to contend with a general age-related decline in plasticity (Werker & Tees, 2005).

The goal of the current study is to explore the distributional phonetic learning ability of infants who have already acquired native phonetic categories. In three experiments, infants were exposed to speech sounds in a distributional learning paradigm (Maye et al., 2002) to assess plasticity in their phonetic perception. Although distributional phonetic learning has been demonstrated at 6–8 months of age, fundamental perceptual changes by 10 months leave open the question of whether these infants' perception will be affected by exposure to new statistical distributions.

EXPERIMENT 1

In the first experiment, 10- to 11-month-old infants were tested on their sensitivity to distributional phonetic learning of voiced versus voiceless unaspirated alveolar stops in a design very similar to that on which 6- to 8-month-olds previously succeeded (Maye et al., 2002). If perception can be modified based on distributional information at this age, exposure to a bimodal, but not a unimodal, distribution should be followed by discrimination of the speech sounds.

Method

Participants

Forty-eight healthy, monolingual 10- to 11-month-old English-learning infants participated (M age = 10 months 26 days, range = 10 months 2 days to 11 months 29 days). Twenty-four infants were randomly assigned to each condition (12 females each). Eleven additional infants were excluded for fussiness ($n = 6$), equipment failure ($n = 2$), parental interference ($n = 2$), and sleeping ($n = 1$).

Stimuli

The target and filler auditory stimuli were originally used in Maye et al. (2002). The phonetic contrast was between the voiced and voiceless unaspirated alveolar stops [d] and [t].[1] One syllable each of [da] and [ta] were produced by a female American-English speaker ([ta] was excised from [sta]), and normalized for amplitude and pitch. Duration was equated by manually excising individual pitch pulses from the longer of the two tokens until both were 375 msec. The tokens each had a 10-msec voicing lag and no prevoicing. The primary acoustic dimension on which

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[1] The voiceless unaspirated [t] occurs after /s/ in English. In English, when /t/ occurs in syllable-initial position it is typically pronounced with aspiration: [t^h]. When English-speaking adults hear unaspirated [t] in syllable-initial position they typically confuse it with [d] (Pegg & Werker, 1997).

they varied was in the onset frequencies of F1 and F2, with a lower F1 (400 Hz) and higher F2 (2,225 Hz) for [da] than for [ta] (F1 of 575 Hz and F2 of 1,700 Hz).[2] These onset frequencies were altered to create an eight-step continuum, with F1 decreasing by 75 Hz and F2 increasing by 25 Hz with each step from [da] to [ta]. In addition, a 90-msec prevoicing was added to the beginning of Token 1, 60 msec to Token 2, and 30 msec to Token 3, while the remaining tokens were not prevoiced (corresponding silences were added to the beginning of Tokens 2–8 to equate release burst timing). All acoustic editing was done using Kay Elemetrics Analysis and Synthesis Laboratory (Lincoln Park, NJ).

Filler stimuli (four naturally produced tokens each of [ma] and [la], ranging 459–472 msec in duration) were included during familiarization to de-highlight the acoustic dimension of interest.

Apparatus

The experiment was conducted in a sound booth (IAC single-walled chamber; Winchester, Hampshire, UK), controlled by a PowerMacintosh G3 computer (Apple, Cupertino, CA) (in an adjoining room) running the program Babyspeech (developed by Dick Aslin, University of Rochester). A digital video camera recorded infant gaze directly to the hard drive of a PowerMacintosh G4. Looking time was coded offline to obtain an optimally accurate frame-by-frame measure of infant attention (30 fps).

Procedure

Parents held their infant on their lap and wore headphones playing music to mask the experimental sounds. The familiarization phase totaled 138 sec, during which infants viewed a silent animated children's video. The audio stimuli consisted of six blocks, each containing 24 randomly ordered tokens: 16 target (bimodal or unimodal distribution) and 8 fillers.

Test trials were maximally 60 sec long, containing eight tokens with 1-sec interstimulus intervals (ISIs) (Maye et al., 2002). Duration was infant-controlled: trials were terminated when the infant looked away from the monitor for more than 2 sec. Four "alternating" trials, featuring alternation of the endpoint tokens (tokens 1 and 8), were interleaved with four "nonalternating" trials, featuring a single token repeated (token 3 or 6). If infants did not discriminate the endpoint tokens, the two types of test trials would appear to be the same (perceived as nonalternating). However, if infants

[2] This is due to coarticulation between [t] and the preceding [s] that is not present for [d], resulting in a slight difference in place of articulation (Pegg & Werker, 1997).

discriminated the endpoint tokens they would perceive the differences between the alternating and nonalternating test trials (Best & Jones, 1998). Familiarization procedures with multiple stimulus tokens typically produce a preference for the nonalternating trials (Maye et al., 2002; Teinonen et al., 2008; Yeung & Werker, 2009). The auditory stimulus for each trial was initiated when the infant fixated on the visual stimulus; a static, unbounded black-and-white checkerboard. Trials on which looking time was less than 1 sec were discarded from analysis.

Results

Average looking times were computed for each infant on alternating and nonalternating trials (see Table 1), which were entered into a two (condition: unimodal or bimodal) × two (test trial type: alternating versus nonalternating) mixed analysis of variance (ANOVA). There was a main effect of condition, with infants in the bimodal condition looking longer, $F(1, 46) = 10.512$, $p = .002$. However, there was no effect of trial type, $F(1, 46) = .006$, $p = .94$, and no interaction, $F(1, 46) = .037$, $p = .85$. Simple main effects confirm that neither infants in the bimodal condition, $F(1, 46) = .037$, $p = .85$, nor those in the unimodal condition, $F(1, 46) = .007$, $p = .94$, discriminated the test trial types.

Discussion

The present results suggest that the same brief amount of distributional information that altered phonetic discrimination at 6–8 months (Maye et al., 2002, 2008) is not sufficient to alter perception by 10–11 months. Interestingly, infants hearing the bimodal distribution looked longer in the test trials than infants hearing the unimodal distribution, the same as found in Maye et al. (2002). Regardless, the 10-month-old infants do not respond to the distributional information by modifying their discrimination. At this stage in language development infants may be more resistant to tuning to a pattern that is in conflict with their typical input.

TABLE 1
Experiment 1: Infants' Average Looking Times (in sec) to Each of the Two Test Trial Types

	Alternating test trials mean (SD)	*Nonalternating test trials mean (SD)*
Bimodal condition	10.57 (6.62)	10.76 (5.51)
Unimodal condition	6.68 (2.99)	6.80 (2.56)

EXPERIMENT 2

A second experiment further explored perceptual plasticity using a Hindi place-of-articulation distinction. This retroflex-dental distinction is reliably discriminated by English-learning infants at 6–8 months of age, but is no longer discriminated at 10 months (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Werker & Lalonde, 1988; Werker & Tees, 1984). If infants of 10 months use distributional learning to direct perception, exposure to a categorical distribution of the sounds should result in subsequent discrimination of the nonnative sounds. In this experiment, slightly younger infants (10 months as opposed to 10–11 months in Experiment 1) were tested to explore plasticity at the cusp of perceptual development.

Method

Participants

Forty-eight healthy, monolingual English-learning infants participated (*M* age = 10 months 13 days, range = 10 months 0 days to 10 months 30 days). Twenty-four were randomly assigned to each condition (12 females each). Fourteen additional infants were excluded for fussiness ($n = 10$), equipment failure ($n = 2$), ear infection ($n = 1$), and parental interference ($n = 1$).

Stimuli

The target stimuli were chosen from five formant tokens from along a synthetic voiced unaspirated dental-retroflex continuum constructed with the Mattingly synthesizer on the VAX 11/780 at Haskins Laboratories (Werker & Lalonde, 1988). Following the values seen in natural tokens (Werker & Tees, 1984) and verified in a labeling experiment with adult Hindi listeners (Werker & Lalonde, 1988), an eight-step continuum was constructed by manipulating the starting frequency of F2 and F3. Token 1 had an F3 onset of 2,576 Hz and an F2 onset of 1,250 Hz, and Token 8 had an F3 onset of 2,912 Hz and an F2 onset of 1,600 Hz. The remaining tokens differed by F3 and F2 in equal steps (i.e., at each step F3 decreased by 48 Hz and F2 increased by 50 Hz). The burst directly preceded the onset of voicing, and lasted 10 msec. The frequency range of the burst was identical for each of the tokens. Each stimulus was 275 msec in duration. Filler stimuli were identical to those used in Experiment 1.

Apparatus

The experiment was conducted in a $280 \times 226\text{-cm}^2$ sound-attenuated room dimly lit by two shaded 60-W floor lamps. The front wall was covered by a black cloth surrounding a television screen with audio speakers hidden to the left and right playing sounds between 68–72 dB(A) SPL. A digital video camera peeked out below the television to relay the infant's image to the control room and record looking behavior for offline coding (30 frames per second). The experiment was controlled by a Macintosh G4 computer with Habit 2000 software (Cohen, Atkison, & Chaput, 2004).

Procedure

The procedure closely followed that of Experiment 1. Each trial was initiated when the infant fixated on the attention-getter stimulus, a flashing, color-changing ball. A pretest trial acquainted infants with the audiovisual set-up. It consisted of female-produced utterances of the nonsense word *pok* and a spinning toy waterwheel. The familiarization phase totaled 112 sec, during which infants viewed a video of dynamic, colorful dots forming a flower shape. As in the first experiment, the audio stimuli consisted of six blocks, each containing 24 randomly ordered tokens: 16 target and 8 fillers, with 500-msec ISIs.

The experimental manipulation was a bimodal distribution. A unimodal distribution has been previously used as comparison (Experiment 1; Maye et al., 2002, 2008), but the current experiment used a flat distribution (equal numbers of each token) as a control. Whereas a unimodal distribution collapses discrimination, a flat distribution is designed to reveal a priori perception. This was desirable with the current age group as it was possible that the 10-month-olds, on the cusp of perceptual reorganization, might retain some residual sensitivity to the nonnative distinction. In that case, discrimination would be collapsed by a unimodal distribution, leaving open the question of which condition was (or whether both conditions were) the experimental manipulation. A flat distribution (where tokens are presented an equivalent number of times), although probably not a naturally occurring distribution, is a more accurate control that familiarizes infants with the tokens without manipulating perception.

The test phase was almost the same as that of Experiment 1. Eight test trials were each 10 sec long, once again containing eight tokens with 1-sec ISIs (Maye et al., 2002). However, the trial length was fixed, rather than infant-controlled, and no trials were discarded from analysis.

TABLE 2
Experiment 2: Infants' Average Looking Times (in sec) to Each of the Two Test Trial Types

	Alternating test trials mean (SD)	*Nonalternating test trials mean (SD)*
Bimodal condition	3.99 (1.86)	4.19 (1.71)
Flat condition	4.98 (1.76)	5.14 (1.76)

Results

Test trial looking times were submitted to a two (condition: bimodal versus flat) × two (test trial type: alternating versus nonalternating) mixed ANOVA. There was a marginal main effect of condition, $F(1, 46) = 3.98$, $p = .052$, with infants in the flat condition looking more than infants in the bimodal condition (see Table 2). There was no main effect of test trial type, $F(1, 46) = 1.49$, $p = .23$, and the interaction was not significant, $F(1, 46) = .029$, $p = .87$. Simple main effects reveal that neither infants in the bimodal condition, $F(1, 46) = .97$, $p = .32$, nor those in the flat condition, $F(1, 46) = .55$, $p = .46$, discriminated the test trials.

Discussion

The looking times in Experiment 2 are shorter than those of Experiment 1 due to the fixing of test trial length at 10 sec, in contrast to the (infant-controlled) maximum 60-sec test trials in Experiment 1. However, like in Experiment 1, the 10-month-old infants did not appear to learn the place-of-articulation contrast. Together, these two experiments suggest that by 10 months of age, brief exposure to nonnative speech distributions is not sufficient to alter infants' phonetic discrimination. This lack of learning stands in contrast to previous work showing that infants of 6–8 months modify their discrimination in response to brief exposure to distributional information (Maye et al., 2002, 2008). The null results in Experiment 2 were obtained even while using dynamic visual stimuli (presumably more engaging than a static visual image used with younger infants; Maye et al., 2002), which has been suggested to facilitate auditory learning (Panneton, McIlreavy, & Aslin, 2009). Further, the null results hold over both a voicing distinction as well as a place-of-articulation distinction, suggesting that the failure generalizes across phonetic contrasts.

EXPERIMENT 3

One contribution to infants' difficulty at 10 months might be that the greater language experience accumulated (compared with at 6–8 months) results in increased perceptual stability. This a priori perceptual learning may require more exposure to be overcome. A final experiment tested the statistical hypothesis that a lengthened exposure period would result in perceptual change by doubling the length of the familiarization phase.

Method

Participants

Ten-month-old healthy, monolingual English-learning infants participated (M age = 10 months 14 days, range = 10 months 0 days to 11 months 2 days). Twenty-four infants were randomly assigned to each condition (12 females in each). Twenty-one additional infants were excluded for fussiness ($n = 19$) and parental interference ($n = 2$).

Procedure

The procedure was identical to Experiment 2, except with two familiarization phases instead of one.

Stimuli

The first familiarization phase was identical to the single familiarization phase of Experiment 1. The second familiarization phase was also the same, except that it presented a static image of tulips (Maye et al., 2002) instead of the dynamic dots.

Results

A two (condition: bimodal versus flat) × two (test trial type: alternating versus nonalternating) mixed ANOVA was calculated. There was no main effect of condition, $F(1, 46) = .48$, $p = .49$, or test trial, $F(1, 46) = 1.64$ $p = .21$, but the interaction was significant, $F(1, 46) = 4.69$, $p = .036$. Simple main effects reveal that infants in the bimodal condition discriminated the test trials, $F(1, 46) = 5.94$, $p = .018$, but those in the flat condition did not, $F(1, 46) = .39$, $p = .53$ (see Table 3).

TABLE 3
Experiment 3: Infants' Average Looking Times (in sec) to Each of the Two Test Trial Types

	Alternating test trials mean (SD)	*Nonalternating test trials mean (SD)*
Bimodal condition	4.68 (1.96)	5.15 (1.96)
Flat condition	5.30 (1.47)	5.18 (1.32)

Discussion

Infants hearing the bimodal distribution demonstrated perceptual learning in response to the lengthened familiarization, later discriminating the nonnative sounds. In contrast to the failure in the first two experiments, these results confirm that phonetic learning at 10 months of age can still be accomplished following a still relatively brief exposure period. The fact that infants successfully modified discrimination following a doubled familiarization, but not with the single familiarization period sufficient for younger infants, suggests that learning becomes more difficult by 10 months of age.

GENERAL DISCUSSION

In three experiments, 10-month-old English-learning infants were briefly exposed to nonnative speech sound distributions to examine phonetic plasticity following perceptual reorganization. In the first two studies, the 10-month-olds did not change their discrimination. This was true regardless of whether a voicing (Experiment 1) or place-of-articulation distinction (Experiment 2) was used. These results contrast with those of 6- and 8-month-olds, where perception was altered after the same length of exposure (Maye et al., 2002, 2008). The third experiment doubled the familiarization time, and after the longer exposure period infants revealed phonetic learning. Importantly, whereas previous distributional learning studies have used voicing contrasts, this learning was found using a place-of-articulation contrast, extending the mechanisms of distributional learning to a new contrast type. Together, these studies show that distributional phonetic learning is still possible in a brief learning period at 10 months. However, the extended learning period necessary to demonstrate this learning, especially in the context of older infants' generally faster learning ability (Hunter & Ames, 1988), suggests that 10-month-olds' perception is less malleable than 6- to 8-month-olds'.

Why might learning be more difficult at 10 months than just 2 months earlier? One difference is the native perceptual sensitivities acquired by this age. Indeed, between 6 and 10 months of age, infants not only maintain, but improve discrimination on native contrasts (Kuhl et al., 2006; Narayan et al., in press). The native phonetic categories that have emerged probably direct perception, helping infants to ignore nonnative distinctions. As native structure has already been established at 10 months (for the distinctions under examination), phonetic change at this age might be less similar to learning a first language (at 6–8 months) and more similar to learning a second language, a notoriously difficult task in adulthood. Relatedly, by 10 months of age, infants would have accumulated significantly more distributional experience in the ambient language environment, statistically stabilizing the native representation.

An increased difficulty at 10 months could also stem from the growing importance of nonphonetic factors in phonetic learning. Distributional phonetic learning might be the most robust type of learning in the first half year of age, but by 10 months, phonetic learning might be facilitated with additional conceptual cues, such as the association of distinct labels with different sound categories (Yeung & Werker, 2009), the association of distinct sounds with different facial articulatory cues (Teinonen et al., 2008), or even the presence of factors, such as social interaction (Kuhl, Tsao, & Liu, 2003) and attention (Conboy, Brooks, Taylor, Meltzoff, & Kuhl, 2008; also see Guion & Pederson, 2007).

The potential underlying reasons for 10-month-olds' difficulty might be teased apart by testing infants on sounds that are outside of native phonetic space, such as click contrasts (Best, McRoberts, & Sithole, 1988). If infants' difficulty stems from the emergence of native phonetic categories, infants' distributional learning of sounds that are unaffected by native reorganization might not suffer by this age. However, if the difficulty stems from the increased importance of contextual factors, a lengthened familiarization would still be necessary to result in phonetic learning.

In summary, the current study demonstrates that although possible, 10-month-olds' distributional phonetic learning is more difficult than 6- to 8-month-olds'. There are a number of factors, including greater native language experience, phonetic categories, and an increased role of contextual factors in learning, which together may contribute to a more demanding learning situation. Understanding the relative contribution of these different factors will not only offer further insights into 10-month-olds' well-documented difficulty with nonnative discrimination, but also suggest potential interventions to help enhance phonetic plasticity in older infants and children who, for various reasons (e.g., adoption, correction of hearing loss), may be exposed to new phonetic information.

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