Developmental Science 9:2 (2006), pp F13–F21

FAST-TRACK REPORT

Infants show a facilitation effect for native language phonetic perception between 6 and 12 months

Patricia K. Kuhl,[1] Erica Stevens,[1] Akiko Hayashi,[2] Toshisada Deguchi,[3] Shigeru Kiritani[4] and Paul Iverson[5]

1. *Institute for Learning and Brain Sciences and Department of Speech and Hearing Sciences, University of Washington, USA*
2. *Research Institute for the Education of Exceptional Children, Gakugei University, Tokyo, Japan*
3. *Comprehensive Educational Science, Gakugei University, Tokyo, Japan*
4. *Institute of Cognitive Sciences in Languages and Cultures, Kobe Kaisei College, Kobe, Japan*
5. *Department of Phonetics and Linguistics, University College London, UK*

Abstract

Patterns of developmental change in phonetic perception are critical to theory development. Many previous studies document a decline in nonnative phonetic perception between 6 and 12 months of age. However, much less experimental attention has been paid to developmental change in native-language phonetic perception over the same time period. We hypothesized that language experience in the first year facilitates native-language phonetic performance between 6 and 12 months of age. We tested 6–8- and 10–12-month-old infants in the United States and Japan to examine native and nonnative patterns of developmental change using the American English /r-l/ contrast. The goals of the experiment were to: (a) determine whether facilitation characterizes native-language phonetic change between 6 and 12 months of age, (b) examine the decline previously observed for nonnative contrasts and (c) test directional asymmetries for consonants. The results show a significant increase in performance for the native-language contrast in the first year, a decline in nonnative perception over the same time period, and indicate directional asymmetries that are constant across age and culture. We argue that neural commitment to native-language phonetic properties explains the pattern of developmental change in the first year.

Introduction

To acquire a specific language, infants have to learn which phonetic distinctions will be used phonemically in their native language. Anchoring this developmental process are two well-established facts: first, early in life, infants are capable of discriminating among many, if not all, the phonetic units of the world's languages, as established by the phenomenon of categorical perception (e.g. Eimas, Siqueland, Jusczyk & Vigorito, 1971; Streeter, 1976), and second, by adulthood, universal phonetic capacity is no longer in place – nonnative phonetic discrimination can be very difficult (e.g. Best, McRoberts & Goodell, 2001; Iverson, Kuhl, Akahane-Yamada, Diesch, Tohkura, Kettermann & Siebert, 2003; Miyawaki, Strange, Verbrugge, Liberman, Jenkins & Fujimura, 1975; Werker & Lalonde, 1988; Zhang, Kuhl, Imada, Kotani & Tohkura, 2005). The mechanism underlying this transition in speech perception has long been the focus of experimentation and theory.

Aslin and Pisoni (1980) described four possible types of developmental change in infants' phonetic perception: maintenance, loss, induction and facilitation. Historically, theories attempting to explain developmental speech perception focused on maintenance and loss, in other words, a model of *selection*. According to this view, phonetic abilities stem from an innate specification of all possible options that are maintained or lost as a function of experience. Classic selectionist views are represented by Eimas' phonetic feature detector account (Eimas, 1975) and Liberman's motor theory (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985). On both accounts, infants are innately endowed with a specification of phonetic units that are subsequently maintained or lost based on experience.

Address for correspondence: Patricia K. Kuhl, Institute for Learning and Brain Sciences, Box 357920, University of Washington, Seattle, WA 98195, USA; e-mail: pkkuhl@u.washington.edu

The selection model lost favor with the discovery of categorical perception for speech in nonhuman animals (Kuhl & Miller, 1975, 1978; Kuhl & Padden, 1982, 1983; see Dooling, Best & Brown, 1995, for relevant bird data), and demonstrations of categorical perception for non-speech stimuli in infants (Jusczyk, Rosner, Cutting, Foard & Smith, 1977; Jusczyk, Pisoni, Walley & Murray, 1980). These data undermined the suggestion that infants' initial capacities were necessarily due to innate mechanisms that defined phonetic units. Moreover, adults remained capable of discriminating nonnative contrasts, suggesting that nonnative abilities are not 'lost' (Carney, Widin & Viemeister, 1977; Pisoni, Aslin, Perey & Hennessy, 1982; Rivera-Gaxiola, Csibra, Johnson & Karmiloff-Smith, 2000; Werker & Logan, 1985; Werker, 1995).

Infant studies produced valuable new information. Werker and her colleagues demonstrated that a decrease in *nonnative* consonant perception occurs between 6–8 and 10–12 months of age (Werker & Tees, 1984). Many additional studies examined nonnative speech perception performance at 6–8 and 10–12 months of age. Data on nine contrasts have now been published, seven of which show a decline in performance with age (Best & McRoberts, 2003; Best, McRoberts, LaFleur & Silver-Isenstadt, 1995; Tsushima, Takizawa, Sasaki, Shiraki, Nishi, Kohno, Menyuk & Best, 1994; Werker & Tees, 1984). Two studies failed to show a decline; American infants showed no decline in the discrimination of African clicks when tested at 6–8, 10–12 and 14 months of age (Best, McRoberts & Sithole, 1988), and French-learning infants tested at 6–8 and 10–12 months on the /d-th/contrast, not phonemic in French, showed no decline in the first year (Polka, Colantonio & Sundara, 2001).

Explanations for the decline in *nonnative* speech perception varied (Best, 1994, 1995; Best & McRoberts, 2003; Burnham, Earnshaw & Clark, 1991; Diamond, Werker & Lalonde, 1994; Lalonde & Werker, 1995; Werker, 1995; Werker & Pegg, 1992). Werker's group related cognitive abilities to nonnative speech perception, showing that infants who have retained the ability to perceive nonnative phonetic contrasts are more likely to make the 'A, not B' error, suggesting that focusing on relevant information is linked across domains (Lalonde & Werker, 1995). Best's Perceptual Assimilation Model (PAM; 1994, 1995; Best & McRoberts, 2003) argued that infants perceive phonetic units in terms of their underlying articulatory gestures, and an update of the model, PAM/AO (Articulatory Organ), argues specifically that nonnative discrimination declines when phonetic contrasts involve the same articulatory organ (/s-z/), as opposed to different articulatory organs (/b-t/). Tests on nonnative perception in 6–8- and 10–12-month-old American infants supported this prediction (Best & McRoberts, 2003).

In contrast to the many infant experiments testing nonnative contrasts, surprisingly little data exist to examine the potential for developmental change in native-language speech perception between 6 and 12 months of age. Only two native-language contrasts have been tested at both ages. Polka *et al.*'s (2001) study tested English-learning infants on the native-language /d-th/ contrast; they observed no change in native-language perception as a function of age during the first year. By the age of 4, however, children tested on the same contrast improved significantly when compared to 10–12-month-old infants (Sundara, Polka & Genesee, in press). The authors explain that additional exposure to these native-language phonetic units may be required to show developmental change because they are acoustically fragile and have unique phonological characteristics (Polka *et al.*, 2001; Sundara *et al.*, in press). Best and McRoberts (2003) also tested the native-language fricative /s-z/, and performance actually declined between 6–8 and 10–12 months of age, though the authors mention that the /s-z/ contrast has been shown to be more difficult to discriminate for infants (Eilers, Wilson & Moore, 1977).

There are thus no behavioral studies on infants indicating improvement in phonetic perception for consonants – *facilitation* – between 6 and 12 months of age. This is surprising, given the plethora of studies on infants who show avid learning of native-language regularities between 6 and 9 months (see Jusczyk, 1997, for review). Learning has been demonstrated during this period for the stress patterns of native-language words (Jusczyk, Cutler & Redanz, 1993) and, of particular relevance to the present tests, learning that relies on phonetic analysis, such as native-language phonotactic patterns (Friederici & Wessels, 1993; Jusczyk, Luce & Charles-Luce, 1994; Mattys, Jusczyk, Luce & Morgan, 1999).

Work and theorizing in this laboratory predicts facilitation for native-language phonetic contrasts in the first year of life based on infants' sensitivity to the distributional and perceptual patterns in language input (Kuhl, 1993, 2000), which result in the formation of phonetic categories with internal structure (Kuhl, 1991; Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992). The Native Language Magnet/Neural Commitment (NLM/NC) model argues that, between 6 and 12 months of age, learning of the acoustic and statistical regularities of ambient speech alters neural tissue; neural connections responding to ambient regularities are strengthened. This *neural commitment* is argued to have bi-directional effects on infants' perception of speech (Kuhl, 2004; Kuhl, Conboy, Padden, Nelson & Pruitt, 2005). It enables the acquisition of more complex patterns (words) that rely on the initially learned regularities, while at the same time suppressing alternative patterns that do not conform to those already learned. The NLM/NC model thus holds that infants should exhibit perceptual growth in native-language phonetic perception during the first year, rather than simply maintenance of their innate abilities.

Indirect support for perceptual growth in the first year is available. First, cross-language studies of vowel perception indicate learning from ambient speech by 6 months of age. English- and Swedish-learning infants tested with English and Swedish vowels showed greater categorization abilities for native- as opposed to foreign-language vowels (Kuhl *et al.*, 1992). Second, 6–8-month-old infants show phonetic learning after exposure to an eight-stimulus continuum in which the frequency of presentation was altered; a bimodal (higher frequency for stimuli near the ends of the continuum) distribution produced discrimination whereas a unimodal (higher frequency of the middle stimuli) distribution did not (Maye, Werker & Gerken, 2002). Third, in a foreign-language intervention study, 9.3-month-old infants showed phonetic learning of a nonnative consonant contrast after exposure to a foreign language (Kuhl, Tsao & Liu, 2003). English-learning infants were exposed to natural Mandarin Chinese during 12 play sessions between 9 and 10 months of age, and, following this intervention, performed significantly above infants in a control group who were equivalently exposed to books and toys but heard only English (Kuhl *et al.*, 2003). Finally, there is evidence of phonetic learning in the first year from studies using brain measures. Rivera-Gaxiola, Silva-Pereyra and Kuhl (2005) showed that the Mismatch Negativity (MMN) increased significantly between 7 and 11 months of age to a native-language consonant change, while decreasing in response to a nonnative contrast. Similar increases/decreases were reported in the neural response to native- and foreign-language vowels between 6 and 12 months (Cheour, Ceponiene, Lehtokoski, Luuk, Allik, Alho & Naatanen, 1998). While these data suggest learning, no behavioral study measuring phonetic perception at 6–8 and 10–12 months has provided direct evidence.

The primary goal of the present experiments, therefore, was to examine developmental change in native and nonnative phonetic perception at 6–8 and 10–12 months of age using a cross-language design. The phonetic contrast used in these studies, American English /r-l/, is a native phonetic contrast for American infants and a nonnative contrast for Japanese infants. English /r/ and /l/ is of interest to Best's model because the /r-l/ contrast is a within-organ contrast. PAM/AO and NLM/NC both predict a decline with age for Japanese infants discriminating the /r-l/ contrast, and an initial test of Japanese infants supports this (Tsushima *et al.*, 1994). Native-language perception of /r-l/, not tested in the Tsushima *et al.* study, presents an interesting case. If AO perception supersedes native-language experience, then American infants tested with the /r-l/ contrast should show a decline (Best & McRoberts, 2003). In contrast, NLM/NC (and perhaps frameworks such as PRIMIR, which also emphasizes distributional cues, see Werker & Curtin, 2005) predicts an increase in performance with age, rather than a decline.

A second goal of the present tests was to examine directional asymmetries in infant speech discrimination. Directional asymmetries are shown when discrimination of a change in one direction results in significantly better performance than in the other direction. In tests using vowel contrasts, infants at 6–8 and 10–12 months of age show significant direction effects across age and culture (Polka & Bohn, 1996, 2003). Infant studies of directional asymmetries of this type have not been conducted for consonants. Testing both directional asymmetries and linguistic effects in the same study has the advantage of controlling for both the stimuli and the participants, which allows the two effects to be compared.

In sum, the present study examined developmental change in infants' perception of consonants between 6 and 12 months using a contrast that was phonemic for one group of infants and non-phonemic for the other. We hypothesized that (a) native listeners would show *facilitation* in phonetic perception with age, (b) nonnative listeners would show a performance decline, though one that evidenced above-chance discrimination at 10–12 months of age and (c) we argued that potential directional effects would be independent of age and culture.

Method

Subjects

Participants were 32 American infants tested in Seattle and 32 Japanese infants tested in Tokyo with identical experimenters, equipment and stimuli. Of the 32 American infants in the final sample, 16 (8 girls) were 6–8 months of age (mean age at test = 6.5 months; range = 6.2 to 6.7 months) and 16 (8 girls) were 10–12 months of age (mean age at test = 11.2 months; range = 11.1 to 11.4 months). Similarly, 16 (8 girls) of the Japanese infants were 6–8 months of age (mean age at test = 6.8 months; range = 6.0 to 7.7 months) and 16 (8 girls) were 10–12 months of age (mean age at test = 10.5 months; range = 10.0 to 12.1 months). An additional 144 infants did not complete testing due to a failure to meet criterion in the pre-established time period (118),[1] crying (11), equipment failure (5) or failure to return for all of the required sessions (10). Criteria for inclusion in the study were that infants had no known visual or auditory deficits, were full term (born +/– 14 days from due date) and normal birth weight (6–10 lb), and that members of their immediate families had no history of hearing loss or language impairment. Parents were paid $30 for their participation.

Stimuli

The stimuli were computer synthesized tokens of American English /ra/ and /la/ syllables used in previous tests on adults, ones easily discriminated by adult native speakers (Iverson *et al.*, 2003). The /ra/ and /la/ syllables were matched in all acoustic details other than the third formant frequency transition, the critical parameter distinguishing American English /ra/ and /la/ tokens. Complete stimulus specifications are described elsewhere (Iverson *et al.*, 2003).

Apparatus

The entire experiment was under computer control; trials, stimulus selection and all contingencies were effected according to the experimental protocol. The speech sounds were reproduced at 10 k 12-bit samples per second, and were low-pass filtered at a 4.6 kHz. Stimuli were amplified and delivered to subjects in a sound-treated room via a studio-quality loudspeaker. Infant responses were monitored in the control room by the experimenter via closed-circuit camera and a video monitor.

Infant testing procedure

A conditioned Head Turn (HT) technique widely used in tests of infant speech perception assessed infant discrimination (Kuhl, 1985). Infants were trained to produce a head turn for visual reinforcement whenever a *background* speech sound, repeated once every two seconds, was changed to a *target* speech sound. For half the infants, /ra/ served as the background and /la/ as the target; for the remaining half, these conditions were reversed. Infants were held on a parent's lap, facing an assistant seated at the infant's right side. The assistant maintained the infant's attention by manipulating a series of engaging, silent toys. A loudspeaker, repeating the background sound, was positioned on the infant's left, between two black Plexiglas boxes containing toy animals that could be animated. When the background sound changed to the target sound, infants were trained to turn toward the loudspeaker and were reinforced by the illumination and animation of the toy in the box. A shaping procedure with an intensity cue was used to teach infants that a head turn during the sound change produced the visual reinforcer (see Kuhl *et al.*, 2003, for details).

Two kinds of trials occur, *Target Trials* during which the target sound is presented and head turns are reinforced, and *Control Trials* during which the target sound is not presented. On Target Trials a head turn is scored as a *Hit* and failure to turn is scored as a *Miss*; on Control Trials, a head turn is scored as a *False Alarm* and failure to turn is scored as a *Correct Rejection*. The Test phase consisted of 30 trials, an equal number of Target and Control Trials, presented in random order. Controls for bias include: (a) trial selection and all contingencies were under computer control, (b) the experimenter (who judges head turns on-line) wore headphones that were deactivated during trials so that the stimulus could not be heard, preventing scoring bias, and (c) the parent and the assistant wore headphones and listened to music that masked the speech to prevent them from influencing infants' responses. Using signal-detection analysis methods, the data were used to calculate a percent correct measure (= (hit% + correct rejection%)/2) and a bias-free sensitivity index, d' (= z(hit) – z(false alarm)).

Results

Infants' scores, both percent correct and d′, were entered into a four-factor analysis of variance to examine the effects of age, language, direction and sex. The results were used to address three specific hypotheses regarding developmental change in infants' perception of speech: (a) native-language perception is characterized by facilitation rather than maintenance between 6 and 12 months of age, (b) nonnative speech perception declines between 6 and 12 months, but remains above chance, and (c) directional asymmetries are independent of age and culture. Sex effects were examined to provide data on this issue.

Figure 1 shows the percent correct scores as a function of age and language group of the infants. The results indicate that between 6 and 8 months of age, American and Japanese infants are equivalent in their

[1] Indications of a directional asymmetry were evident even during the training phase of the experiment. The unusually large number of infants who failed to meet criterion was due to a directional asymmetry. Of the 118 infants who failed to meet criterion, 96 infants (81%) were tested in the difficult direction (/ra/background); this effect was observed in both populations at both ages.

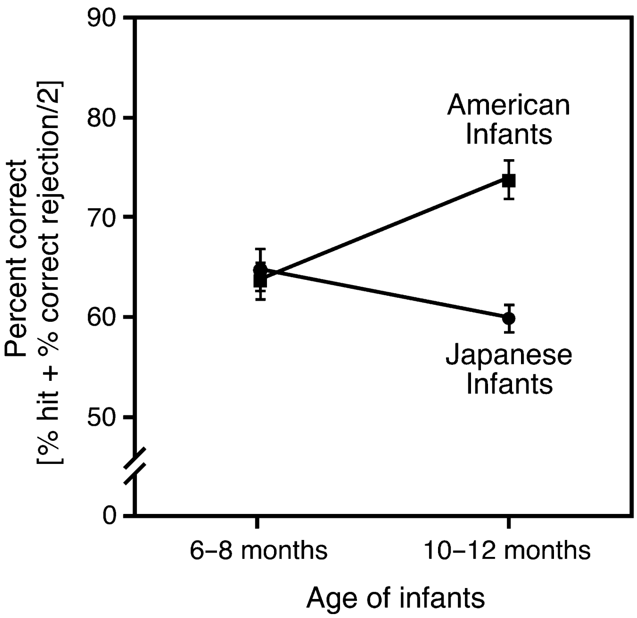

Figure 1 *Effects of age on discrimination of the American English /ra-la/ phonetic contrast by American and Japanese infants at 6–8 and 10–12 months of age. Mean percent correct scores are shown with standard errors indicated.*

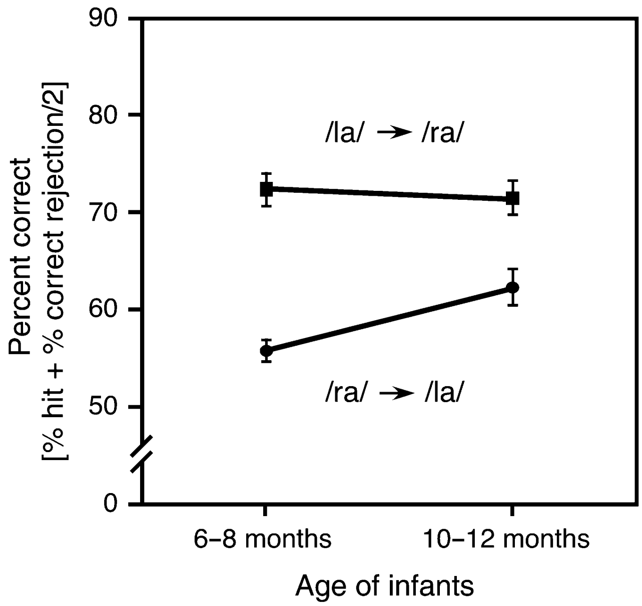

Figure 2 *Effects of the direction of stimulus change (easy = /la-ra/ versus difficult = /ra-la/) on discrimination performance for American and Japanese infants at 6–8 and 10–12 months of age. Mean percent correct scores are shown with standard errors indicated.*

discrimination of the American English /ra-la/ stimuli, performing at approximately 65% correct, significantly above chance (which is 50%, $p < .05$). As predicted, the data indicate that increasing age affects discrimination capacity very differently in the two language groups. American infants demonstrate a substantial increase in their performance on the discrimination task, from 63.7% correct to 73.8% correct. In contrast, Japanese infants showed a decrease from 64.7% correct to 59.9% correct. Analysis of variance confirmed that neither the main effect of age, $F(1, 48) = .68$, $p > .10$, nor that of language, $F(1, 48) = 3.96$, $p > .05$, was significant. However, as predicted, the age × language interaction was significant, $F(1, 48) = 5.30$, $p < .05$. Simple effects follow-up analyses revealed that the effect of age for the American infants was significant, $F(1, 24) = 4.32$, $p < .05$, and not for the Japanese infants, $F(1, 24) = 1.26$, $p > .10$. Japanese infants' performance remained above chance at 10–12 months of age, $p < .05$. The ANOVA revealed no other significant interactions regarding age or language ($p > .10$ in all cases). Analyses using infants' d′ scores produced an identical pattern of results.

Figure 2 displays the percent correct scores for each language group as a function of direction of stimulus change. Half of all infants were tested with /ra/ as the background; the other half heard /la/ as the background. The effect of the direction was dramatic and pervasive. Regardless of age or language experience, infants found it more difficult to detect a stimulus change from /ra/ to /la/ than the reverse. Infants in both groups at both ages demonstrated the effect, as shown by a main effect of stimulus direction, $F(1, 48) = 16.10$, $p < .001$. There were no significant two-way or three-way interactions involving direction of stimulus change. American infants showed an increase in performance over time in both directions, while Japanese infants showed a decrease over time in both directions. No effects of gender were observed in any of the analyses (effects > .10 in all cases).

Discussion

The present experiment addressed the developmental change in infant speech perception brought about by linguistic experience, and examined directional asymmetries using the same stimuli and infants. Data analysis focused on three predictions: (a) infants for whom the American English /r-l/ contrast was native would demonstrate a new pattern in developmental speech perception – one consistent with facilitation – by showing a significant increase in performance between 6 and 12 months of age; (b) when the same phonetic stimuli were nonnative, infants would show the pattern of decline over time seen in numerous other studies, but would remain above chance in their performance; and

(c) directional asymmetries would be observed across age and culture. To provide data on potential sex differences, we also examined gender effects, though none were obtained.

Effects of age and language experience: facilitation for native, decline for nonnative

The data demonstrate that performance on the /r-l/ contrast is equivalent for American and Japanese infants at 6–8 months. By 10–12 months of age, American infants' performance improves significantly when compared to performance at 6–8 months of age, a pattern consistent with perceptual learning and native-language facilitation before the end of the first year. Infants' performance at 6–8 months, though above chance, is well below that of adult native speakers for this contrast (Zhang *et al.*, 2005). This finding supports those of other investigators indicating that infant performance is substantially reduced when compared to adults' (Nittrouer, 2001; Polka *et al.*, 2001; Sundara *et al.*, in press).

The present results are significant in that facilitation for native-language phonetic units, though previously shown *after* the first year and before adulthood (Polka *et al.*, 2001; Sundara *et al.*, in press), has not previously been shown during the first year of life. Two earlier studies suggested either maintenance (Polka *et al.*, 2001), or decline (Best & McRoberts, 2003), but tested either difficult-to-discriminate consonants (/s-z/), or those (such as /th/) that primarily occur in function words (Morgan, Shi & Allopenna, 1996), which are less preferred by 6-month-old infants when compared to content words (Shi & Werker, 2001). These factors may explain why previous studies failed to show a pattern of facilitation for native-language perception during the first year of life (see Burnham, 1986; Sundara *et al.*, in press, for discussion).

Over the same developmental period, Japanese infants show a decline in performance, consistent with many previous studies (Tsushima *et al.*, 1994; Werker & Tees, 1984). Our data indicate that Japanese infants at 10–12 months remain capable of performing above chance on the nonnative phonetic contrast. This result is in line with adult studies showing above-chance performance on nonnative phonetic contrasts measured either behaviorally (Iverson *et al.*, 2003; Pisoni *et al.*, 1982; Werker & Lalonde, 1988; Werker & Tees, 1984), or with neural methods (Rivera-Gaxiola *et al.*, 2000; Zhang *et al.*, 2005) and are also consistent with recent ERP studies providing neural evidence that infants remain capable of discriminating nonnative speech contrasts at 10–12 months (Rivera-Gaxiola *et al.*, 2005).

A second study completed in this laboratory replicates the pattern of results seen here (Tsao, Liu & Kuhl, under review). In the Tsao *et al.* study, developmental change in English- and Mandarin-learning infants was tested using a Mandarin Chinese affricate-fricative contrast at 6–8 months and 10–12 months. American and Chinese infants exhibit equivalent performance at 6–8 months of age that diverges at 10–12 months, with Taiwanese infants showing a significant increase in native-language speech perception performance over time while American infants show a decline, though remaining above chance, at 10–12 months. Moreover, in a second experiment, American infants tested with an English affricate-fricative contrast exhibited a significant increase in performance between 6–8 and 10–12 months of age. Thus, facilitation for native-language contrasts between 6 and 12 months of age has been observed with three different contrasts and infants from two different cultures.

The linguistic effects observed over time thus indicate a double dissociation between native- and nonnative speech perception. According to NLM/NC, native-language phonetic learning enables word learning; moreover, native-phonetic facilitation and nonnative decline are linked (Kuhl, 2004; Kuhl *et al.*, 2005). These claims are supported by two recent studies examining individual infants' native and nonnative speech perception and the degree to which early measures of speech perception predict infants' future language skills (Kuhl *et al.*, 2005; Tsao, Liu & Kuhl, 2004). Tsao *et al.* (2004) demonstrated for the first time that individual differences in speech perception at 6 months of age predict infants' future language abilities at 13, 16 and 24 months of age. Left unresolved by the study was whether the observed association between early speech and later language was attributable to differences in infants' more general auditory or cognitive abilities, or were, as hypothesized, due to a link between early phonetic perception and later language abilities.

The latter claim is supported by a more recent study. In Kuhl *et al.* (2005), 7-month-old infants were tested on both native and nonnative phonetic perception. Two findings were of interest. First, individual infants' performance on the native and nonnative contrasts was negatively correlated; better performance on the native contrast was associated with poorer performance on the nonnative contrast. Second, both native and nonnative performance at 7 months of age predicted future language abilities, but in opposite directions. Better native phonetic perception predicted accelerated language development at 14, 18, 24 and 30 months of age, whereas better nonnative performance predicted slower language development at the same four future points in time (Kuhl *et al.*, 2005). The findings of Tsao *et al.* (2004) and Kuhl *et al.* (2005) support the idea that the association between early phonetic perception and later language is causal, and suggest that the observed perceptual improvement in native language phonetic perception between 6 and 12 months is an important developmental step toward language for infants.

We have argued that the relationship between early *native* vs. *nonnative* speech perception and later language is attributable to infants' neural commitment to the properties of native language phonetic units (Kuhl, 2004; Kuhl *et al.*, 2005). Neural commitment enhances the detection of more complex linguistic patterns (such as words) that build on learned native-language phonetic units, while suppressing the detection of patterns that do not conform. Infants who have begun the process of native phonetic learning by 7 months show rapid acquisition of words and grammar, while those who continue to excel at nonnative discrimination at 7 months of age (in the absence of exposure to that language) remain in the initial universal stage of phonetic perception – uncommitted – and this is reflected in slower language growth.

A caveat regarding phonetic learning during this period deserves mention. Optimal conditions for robust and long-lasting phonetic learning in infancy are likely to include social interaction. As mentioned previously, infants can learn phonetically from natural exposure to a second language at 9 months of age; however, a second experiment in that report showed that no learning from foreign-language exposure occurs when language is presented via TV or audiotape (Kuhl *et al.*, 2003). Natural phonetic learning may require a social context, despite the fact that simple (and likely short-term) phonetic learning can be demonstrated in the absence of a social context (e.g. Maye *et al.*, 2002). Another social response to infants – the exaggeration of relevant phonetic differences by adult speakers during infant-directed speech (Burnham, Kitamura & Vollmer-Conna, 2002; Kuhl, Andruski, Chistovich, Chistovich, Kozhevnikova, Ryskina, Stolyarova, Sundberg & Lacerda, 1997; Liu, Kuhl & Tsao, 2003) – is a potential agent of change supporting facilitation in native-language speech perception. Infants' skills in tests of speech perception at both 6–8 and 10–12 months of age show a strong association with the degree to which their mothers exaggerate the acoustic-phonetic properties of speech (Liu *et al.*, 2003). While infant-directed speech is apparently not sufficient when presented from a disembodied source (Kuhl *et al.*, 2003), it may play a role in facilitating phonetic learning in natural settings.

Effects of age and language experience on directional asymmetries

The experiment produced a second clear result. Directional asymmetries for the American English /r-l/ consonant stimuli are exhibited regardless of the language background or age of the infants. This finding supports and extends the Polka and Bohn (1996, 2003) results. The present data provide the first cross-cultural results on directional asymmetries for a consonant contrast, and dissociate directional effects from those of language experience. It remains for future experiments to determine why directional asymmetries exist; as discussed in detail by Polka and Bohn (2003), they could reflect either general auditory perception or a bias that is linguistic in nature (see Miller & Eimas, 1996). In the present case, changing the vowel context in which the /r-l/ stimuli are presented would allow us to examine a potential psychoacoustic explanation for the directional asymmetry observed here. The high-frequency formant transitions of /la/ would be more easily affected by forward masking from the spectrally compact /a/ vowel formants than would be the case for the low-frequency formant transitions of /ra/. However, if the /r-l/ contrast was tested in the context of the vowel /i/, with its diffuse formants, no differential temporal masking effects should be observed. We are currently testing this hypothesis.

In summary, infants tested in a standard behavioral paradigm show, for the first time, a pattern suggesting facilitation for native-language phonetic contrasts between 6 and 12 months of age. Infants at the same age tested on the same phonetic contrast, nonnative in their language, show the previously observed pattern of decline with age, and one in which performance remains above chance. Moreover, the study revealed directional asymmetries for consonant stimuli for the first time, and showed that they do not differ across age and culture in infancy. The present results are consistent with the view that exposure to a specific language causes neural commitment to the properties of native-language phonetic units, and that this learning process plays a role in the decline of nonnative phonetic perception.

Acknowledgements

The research reported here was supported by a grant to PKK from the National Institutes of Health (HD 37954), by NIH UW Research Core grants (P30 DC04661 and P30 HD02274), and by Gakugei University, Tokyo, Japan.

References

Aslin, R.N., & Pisoni, D.B. (1980). Some developmental processes in speech perception. In G.H. Yeni-Komshian, J. Kavanagh & C.A. Ferguson (Eds.), *Child phonology: Perception* (Vol. 2, pp. 67–96). New York: Academic Press.

Best, C.T. (1994). The emergence of native-language phonological influences in infants: a perceptual assimilation model. In

J. Goodman & H.C. Nusbaum (Eds.), *The development of speech perception: The transition from speech to spoken words* (pp. 167–224). Cambridge, MA: MIT Press.

Best, C.T. (1995). A direct realist view of cross-language speech perception. In W. Strange (Ed.), *Speech perception and linguistic experience: Issues in cross-language research* (pp. 171–204). York Timonium, MD: York Press.

Best, C.T., & McRoberts, G.W. (2003). Infant perception of non-native consonant contrasts that adults assimilate in different ways. *Language and Speech*, **46**, 183–216.

Best, C.T., McRoberts, G.W., & Goodell, E. (2001). American listeners' perception of non-native consonant contrasts varying in perceptual assimilation to English phonology. *Journal of the Acoustical Society of America*, **109**, 775–794.

Best, C.T., McRoberts, G.W., LaFleur, R., & Silver-Isenstadt, J. (1995). Divergent developmental patterns for infants' perception of two non-native consonant contrasts. *Infant Behavior and Development*, **18**, 339–350.

Best, C.T., McRoberts, G.W., & Sithole, N.M. (1988). Examination of perceptual reorganization for non-native speech contrasts: Zulu click discrimination by English-speaking adults and infants. *Journal of Experimental Psychology: Human Perception and Performance*, **14**, 345–360.

Burnham, D.K. (1986). Developmental loss of speech perception: exposure to and experience with first language. *Applied Psycholinguistics*, **7**, 207–239.

Burnham, D.K., Earnshaw, L.J., & Clark, J.E. (1991). Development of categorical identification of native and non-native bilabial stops: infants, children and adults. *Journal of Child Language*, **18**, 231–260.

Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2002). What's new, pussycat? On talking to babies and animals. *Science*, **296**, 1435.

Carney, A.E., Widin, G.P., & Viemeister, N.F. (1977). Noncategorical perception of stop consonants differing in VOT. *Journal of the Acoustical Society of America*, **62**, 961–970.

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Naatanen, R. (1998). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience*, **1**, 351–353.

Diamond, A., Werker, J.F., & Lalonde, C. (1994). Toward understanding commonalities in the development of object search, detour navigation, categorization, and speech perception. In G. Dawson & K.W. Fischer (Eds.), *Human behavior and the developing brain* (pp. 380–426). New York: Guilford Press.

Dooling, R.J., Best, C.T., & Brown, S.D. (1995). Discrimination of synthetic full-formant and sinewave /ra-la/ continua by budgerigars (*Melopsittacus undulatus*) and zebra finches (*Taeniopygia guttata*). *Journal of the Acoustical Society of America*, **97**, 1839–1846.

Eilers, R.E., Wilson, W.R., & Moore, J.R. (1977). Developmental changes in speech discrimination in infants. *Journal of Speech and Hearing Research*, **20**, 766–780.

Eimas, P.D. (1975). Speech perception in early infancy. In L.B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognitio*n Vol. II. (pp. 193–231). New York: Academic Press.

Eimas, P.D., Siqueland, E.R., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, **171**, 971–974.

Friederici, A.D., & Wessels, J.M.I. (1993). Phonotactic knowledge of word boundaries and its use in infant speech perception. *Perception and Psychophysics*, **54**, 287–295.

Iverson, P., Kuhl, P.K., Akahane-Yamada, R., Diesch, E., Tohkura, Y., Kettermann, A., & Siebert, C. (2003). A perceptual interference account of acquisition difficulties for non-native phonemes. *Cognition*, **87**, B47–B57.

Jusczyk, P.W. (1997). *The discovery of spoken language*. Cambridge, MA: MIT Press.

Jusczyk, P.W., Cutler, A., & Redanz, N.J. (1993). Infants' preference for the predominant stress patterns of English words. *Child Development*, **64**, 675–687.

Jusczyk, P.W., Luce, P.A., & Charles-Luce, J. (1994). Infants' sensitivity to phonotactic patterns in the native language. *Journal of Memory and Language*, **33**, 630–645.

Jusczyk, P.W., Pisoni, D.B., Walley, A., & Murray, J. (1980). Discrimination of relative onset time of two-component tones by infants. *Journal of the Acoustical Society of America*, **67**, 262–270.

Jusczyk, P.W., Rosner, B.S., Cutting, J.E., Foard, C.F., & Smith, L.B. (1977). Categorical perception of nonspeech sounds by 2-month-old infants. *Perception and Psychophysics*, **21**, 50–54.

Kuhl, P.K. (1985). Methods in the study of infant speech perception. In G. Gottlieb & N. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life: A methodological overview* (pp. 223–251). Norwood, NJ: Ablex.

Kuhl, P.K. (1991). Human adults and human infants show a 'perceptual magnet effect' for the prototypes of speech categories, monkeys do not. *Perception and Psychophysics*, **50**, 93–107.

Kuhl, P.K. (1993). Early linguistic experience and phonetic perception: implications for theories of developmental speech perception. *Journal of Phonetics*, **21**, 125–139.

Kuhl, P.K. (2000). A new view of language acquisition. *Proceedings of the National Academy of Sciences*, **97**, 11850–11857.

Kuhl, P.K. (2004). Early language acquisition: cracking the speech code. *Nature Reviews Neuroscience*, **5**, 831–843.

Kuhl, P.K., Andruski, J.E., Chistovich, I.A., Chistovich, L.A., Kozhevnikova, E.V., Ryskina, Stolyarova, E.I., Sundberg, U., & Lacerda, F. (1997). Cross-language analysis of phonetic units in language addressed to infants. *Science*, **277**, 684–686.

Kuhl, P.K., Conboy, B., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: implications for the 'critical period'. *Language Learning and Development*, **1**, 237–264.

Kuhl, P.K., & Miller, J.D. (1975). Speech perception by the chinchilla: voiced–voiceless distinction in alveolar plosive consonants. *Science*, **190**, 69–72.

Kuhl, P.K., & Miller, J.D. (1978). Speech perception by the chinchilla: identification functions for synthetic VOT stimuli. *Journal of the Acoustical Society of America*, **63**, 905–917.

Kuhl, P.K., & Padden, D.M. (1982). Enhanced discriminability at the phonetic boundaries for the voicing feature in macaques. *Perception and Psychophysics*, **32**, 542–550.

Kuhl, P.K., & Padden, D.M. (1983). Enhanced discriminability at the phonetic boundaries for the place feature in macaques. *Journal of the Acoustical Society of America*, **73**, 1003–1010.

Kuhl, P.K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy: effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences*, **100**, 9096–9101.

Kuhl, P.K., Williams, K.A., Lacerda, F., Stevens, K.N., & Lindblom, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, **255**, 606–608.

Lalonde, C.E., & Werker, J.F. (1995). Cognitive influences on cross-language speech perception in infancy. *Infant Behavior and Development*, **18**, 459–475.

Liberman, A.M., Cooper, F.S., Shankweiler, D.P., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review*, **74**, 431–461.

Liberman, A.M., & Mattingly, I.G. (1985). The motor theory of speech perception revised. *Cognition*, **21**, 1–36.

Liu, H.-M., Kuhl, P.K., & Tsao, F.M. (2003). An association between mothers' speech clarity and infants' speech discrimination skills. *Developmental Science*, **6**, F1–F10.

Mattys, S.L., Jusczyk, P.W., Luce, P.A., & Morgan, J.L. (1999). Phonotactic and prosodic effects on word segmentation in infants. *Cognitive Psychology*, **38**, 465–494.

Maye, J., Werker, J.F., & Gerken, L. (2002). Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition*, **82**, B101–B111.

Miller, J.L., & Eimas, P.D. (1996). Internal structure of voicing categories in early infancy. *Perception and Psychophysics*, **38**, 1157–1167.

Miyawaki, K., Strange, W., Verbrugge, R.R., Liberman, A.M., Jenkins, J.J., & Fujimura, O. (1975). An effect of linguistic experience: the discrimination of [r] and [l] by native speakers of Japanese and English. *Perception and Psychophysics*, **18**, 331–340.

Morgan, J.L., Shi, R., & Allopenna, P. (1996). Perceptual bases of rudimentary grammatical categories. In J.L. Morgan & K. Demuth (Eds.), *Signal to syntax* (pp. 263–286). Mahwah, NJ: Lawrence Erlbaum Associates.

Nittrouer, S. (2001). Challenging the notion of innate phonetic boundaries. *Journal of the Acoustical Society of America*, **110**, 1598–1605.

Pisoni, D.B., Aslin, R.N., Perey, A.J., & Hennessy, B.L. (1982). Some effects of laboratory training on identification and discrimination of voicing contrasts in stop consonants. *Journal of Experimental Psychology: Human Perception and Performance*, **8**, 297–314.

Polka, L., & Bohn, O.-S. (1996). A cross-language comparison of vowel perception in English-learning and German-learning infants. *Journal of the Acoustical Society of America*, **100**, 577–592.

Polka, L., & Bohn, O.-S. (2003). Asymmetries in vowel perception. *Speech Communication*, **41**, 221–231.

Polka, L., Colantonio, C., & Sundara, M. (2001). A cross-language comparison of /d/-/th/ perception: evidence for a new developmental pattern. *Journal of the Acoustical Society of America*, **109**, 2190–2201.

Rivera-Gaxiola, M., Csibra, G., Johnson, M.H., & Karmiloff-Smith, A. (2000). Electrophysiological correlates of cross-linguistic speech perception in adults. *Behavioral Brain Research*, **111**, 11–23.

Rivera-Gaxiola, M., Silva-Pereyra, J., & Kuhl, P.K. (2005). Brain potentials to native- and non-native speech contrasts in seven- and eleven-month-old American infants. *Developmental Science*, **8**, 162–172.

Shi, R., & Werker, J.F. (2001). Six-month-old infants' preference for lexical words. *Psychological Science*, **12**, 70–75.

Streeter, L.A. (1976). Language experience of two-month-old infants shows effects of both innate mechanisms and experience. *Nature*, **259**, 39–41.

Sundara, M., Polka, L., & Genesee, F. (in press). Language-experience facilitates discrimination of /d-th/ in monolingual and bilingual acquisition of English. *Cognition*.

Tsao, F.M., Liu, H.M., & Kuhl, P.K. (2004). Speech perception in infancy predicts language development in the second year of life: a longitudinal study. *Child Development*, **75**, 1067–1084.

Tsao, F.M., Liu, H.M., & Kuhl, P.K. (under review). Perception of native and nonnative affricative-fricative contrasts: cross-language tests on adults and infants.

Tsushima, T., Takizawa, O., Sasaki, M., Shiraki, S., Nishi, K., Kohno, M., Menyuk, P., & Best, C. (1994). Discrimination of English /r-l/ and /w-y/ by Japanese infants at 6–12 months: language-specific developmental changes in speech perception abilities. *1994 International Conference on Spoken Language Processing* (pp. 1695–1698), Yokohama, Japan.

Werker, J.F. (1995). Exploring developmental changes in cross-language speech perception. In D. Osherson, L. Gleitman & M. Liberman (Vol. Eds.), *An invitation to cognitive science, Part I: Language* (pp. 87–106). Cambridge, MA: MIT Press.

Werker, J.F., & Curtin, S. (2005). PRIMIR: a developmental model of speech processing. *Language Learning and Development*, **1**, 197–234.

Werker, J.F., & Lalonde, C. (1988). Cross-language speech perception: initial capabilities and developmental change. *Developmental Psychology*, **24**, 672–683.

Werker, J.F., & Logan, J.S. (1985). Cross-language evidence for three factors in speech perception. *Perception and Psychophysics*, **37**, 35–44.

Werker, J.F., & Pegg, J.E. (1992). Infant speech perception and phonological acquisition. In C. Ferguson, L. Menn & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, and implications* (pp. 285–311). York Timonium, MD: York Press.

Werker, J.F., & Tees, R.C. (1984). Cross-language speech perception: evidence for perceptual reorganization during the first year of life. *Infant Behavior anad Development*, **7**, 49–63.

Zhang, Y., Kuhl, P.K., Imada, T., Kotani, M., & Tohkura, Y. (2005). Effects of language experience: neural commitment to language-specific auditory patterns. *NeuroImage*, **26**, 703–720.

Received: 23 September 2005
Accepted: 8 November 2005