A cross-language comparison of /d/–/ð/ perception: Evidence for a new developmental pattern

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Previous studies have shown that infants perceptually differentiate certain non-native contrasts at 6–8 months but not at 10–12 months of age, whereas differentiation is evident at both ages in infants for whom the test contrasts are native. These findings reveal a language-specific bias to be emerging during the first year of life. A developmental decline is not observed for all non-native contrasts, but it has been consistently reported for every contrast in which language effects are observed in adults. In the present study differentiation of English /d–ð/ by English- and French-speaking adults and English- and French-learning infants at two ages (6–8 and 10–12 months) was compared using the conditioned headturn procedure. Two findings emerged. First, perceptual differentiation was unaffected by language experience in the first year of life, despite robust evidence of language effects in adulthood. Second, language experience had a facilitative effect on performance after 12 months, whereas performance remained unchanged in the absence of specific language experience. These data are clearly inconsistent with previous studies as well as predictions based on a conceptual framework proposed by Burnham [Appl. Psycholing. **7**, 201–240 (1986)]. Factors contributing to these developmental patterns include the acoustic properties of /d–ð/, the phonotactic uniqueness of English /ð/, and the influence of lexical knowledge on phonetic processing. © *2001 Acoustical Society of America.* [DOI: 10.1121/1.1362689]

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I. INTRODUCTION

One of the major accomplishments of early childhood is learning to understand one or more languages. As a first step, the infant faces the challenge of learning to recognize the meaningful patterns in the speech stream, including the segmental units that distinguish words in their native language. We now know that infants come well equipped for this task. Numerous studies show that infants as young as 1 month of age are already able to differentiate[1] a wide range of phonetic contrasts including native contrasts and non-native contrasts that are difficult for adults to distinguish (e.g., Eimas *et al.*, 1971; for a review see Best, 1994a). Research has also firmly established that these initial perceptual abilities appear to shift from an unconstrained, language-general form towards a more restricted, language-specific pattern by the end of the first year of life. This conclusion is supported by evidence that infants can differentiate certain non-native contrasts at 6–8 months of age but not at 10–12 months, whereas a decline is not observed in infants for whom the test contrasts are native. This finding was first reported by Werker and colleagues. They investigated the effects of age and language experience on cross-language phonetic perception in a series of studies using the conditioned headturn procedure (Werker *et al.*, 1981; Werker and Tees, 1983, 1984a). They tested English-learning infants at several ages on several non-native contrasts including the Hindi retroflex versus dental stop contrast, /ṭ–t̪/, the Hindi voiceless aspirated versus breathy voiced contrast, /t^h–d^h/ and the Salish (Nthlakampx) glottalized velar versus uvular ejective stop contrast, /k′–q′/. The results clearly showed that English-learning infants at 6–8 months of age were able to differentiate these non-native phonetic contrasts even though English adults could not, and that 10- to 12-month-old English infants exhibited a decline in perception of these non-native contrasts when compared to infants in the younger age group. They subsequently replicated this pattern using a longitudinal design and also tested three 11- to 12-month-olds from a Hindi-speaking family and three 11- to 12-month-olds from a Salish-speaking family. The results confirmed the language-specific nature of the decline in perceptual abilities between 6 and 12 months of age. More recently, the same pattern of decline has also been shown using a habituation/dishabituation procedure for English infants tested on the Salish contrast (Best *et al.*, 1995) and for Japanese infants tested on English /r–l/ (Tsushima *et al.*, 1994), a contrast which is notoriously difficult for Japanese adults.

A decline in perceptual differentiation in the first year has also been shown in English-learning infants for several non-native vowel contrasts, including Norwegian /y–ʉ/ (Best *et al.*, 1997) and the German /u–y/ and /U–Y/ (Polka and Werker, 1994). In the latter study, language effects emerged between 4 and 6 months of age, suggesting that language effects begin to emerge earlier in development for vowel contrasts than for consonant contrasts (see also Kuhl *et al.*, 1992). Best (1995; Best *et al.*, 1990) has also reported poor perceptual differentiation by English-learning infants at 10–12 months of age for several additional non-native con-

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sonant contrasts from Zulu, including a lateral fricative voicing contrast, a velar voiceless aspirated versus ejective stop contrast, and a plosive versus explosive bilabial stop contrast. For the Norwegian and the German vowel contrasts and for two of these Zulu contrasts, English adults' differentiation of the non-native contrasts was very good, indicating that infant perception may decline even when language effects are not evident in adults.

Several studies have reported there to be no evidence of a perceptual decline for certain other non-native contrasts in the first year of life. One study using a visual habituation procedure (Best *et al.*, 1988) showed that English adults and English infants between 6 and 14 months of age were able to differentiate the non-native Zulu apical/lateral click consonant contrast. These sounds are unlike any English phonetic category, and English adults did not even perceive them as speech. Best (1991; Best *et al.*, 1990) reported that both English adults and English 10- to 12-month-olds were able to differentiate the Ethiopian ejective /p′–t′/ contrast. Likewise, using the conditioned headturn procedure, Polka and Bohn (1996) failed to find any effects of age or language experience when English-learning and German-learning infants at both 6–8 and 10–12 months of age were tested on the English /æ–ɛ/ contrast, which is not phonemic in German, and the German /u–y/ contrast, which is not phonemic in English.[2] German and English infants showed good differentiation on both contrasts; adult perception of the non-native contrasts in these studies was also very good. These studies confirm that a simple loss-due-to-lack-of-exposure or lack-of-attention explanation is inadequate to account for developmental changes in phonetic perception.

Overall, the findings to date have been taken as evidence that for some phonetic contrasts language experience serves to maintain perceptual differentiation in the first year of life, which otherwise declines when relevant language experience is lacking. However, it is important to note that absence of language experience does not lead to a complete loss in perception. As mentioned above, infants have shown declines for non-native contrasts that non-native adults can easily differentiate. As well, training studies with adults have shown that differentiation of difficult and rarely heard non-native contrasts can be achieved with sufficient training (e.g., Jamieson and Morosan, 1986; Logan *et al.*, 1991; Morosan and Jamieson, 1989; Pisoni *et al.*, 1982; Tees and Werker, 1984) or when sensitive testing procedures are employed (e.g., Werker and Tees, 1984b). Several other findings also argue against an interpretation of developmental decline as a simple effect of exposure. Pegg and Werker (1997) found that perceptual differentiation also declines between 6–8 and 10–12 months for a contrast that has an allophonic status in the native language. This finding highlights the importance of functional status of the phoneme contrast rather than mere allophonic exposure to maintain perception. Lalonde and Werker (1995) have also shown that developmental decline in phonetic perception occurs in synchrony with age-related advances in general cognitive abilities such as visual categorization and object permanence. Taken together these findings argue for an interpretation of age-related changes in cross-language speech perception as a functional reorganization of phonetic perception that reflects advances in linguistic processing (Werker and Pegg, 1992; Werker *et al.*, 1995).

The finding that differentiation declines between 6 and 12 months for some non-native contrasts but not for others is clearly established in the literature, but is not yet well explained. The fact that decline is observed during infancy for non-native contrasts that are easily differentiated by adults reveals that, although infants are beginning to recognize some segmental aspects of their native language, their perceptual structures are still immature. It is not clear whether infants are simply able to recognize some phonetic categories and not others, or whether infants have formed any categories that are comparable to mature listeners. A better understanding of the facts that underlie divergent development patterns in cross-language phonetic perception can help address this issue.

Best (1995) has proposed that, for adults, language effects are evident for some contrasts but not others because there are differences in the way in which the contrasting non-native phones relate to the native phonology. She has developed a perceptual assimilation model (PAM) that is able to account for some differences in adult differentiation based on assimilation patterns (Best, 1990, 1993, 1994a, 1994b). Although it is difficult to assess assimilation patterns in infants, it may be possible to gain some understanding of how the native phonology is beginning to shape perception during infancy by comparing adult and infant differentiation for non-native contrasts that conform to different assimilation patterns in adults. To date, this line of investigation has shown that perceptual declines occur with non-native contrasts that adults assimilate equally well to the same native phonological category, referred to as a single category assimilation (Best *et al.*, 1995). In comparison, perceptual differentiation is maintained for controls that cannot be assimilated within the native phonological space, referred to as a nonassimilated (NA) pattern, such as the Zulu click contrast mentioned above (Best *et al.*, 1988). However, results are inconsistent for two other assimilation patterns. Different outcomes have been reported for contrasts in which each phone is a good match to a different native category, referred to as a two-category (TC) pattern. Specifically, Best found that English infants at 10–12 months were able to discriminate the Ethiopian /p′–t′/ contrast but not the Norwegian /y–ʉ/ contrast or the Zulu lateral fricative voicing contrast; all three of these contrasts conformed to a TC assimilation pattern for English adults. Likewise, results are also inconsistent for contrasts in which both phones are assimilated to a single native category but differ in goodness of fit, referred to as a category-goodness (CG) pattern. Specifically, Polka and Werker (1994) found a decline for two CG vowel contrasts, whereas Polka and Bohn (1996) found that differentiation was maintained for two other CG vowel contrasts. Best also found poor performance at 10–12 months for the Zulu voiceless aspirated versus ejective stop contrast; English adults assimilated this contrast as a CG pattern (Best, 1995). Clearly, more research involving a wider range of non-native contrasts is needed to extend and refine PAM to explain phonetic perception in infancy.

Burnham (1986) has provided a more specific prediction regarding developmental patterns for different phoneme contrasts which is based on their relative position on a ''robust–fragile'' continuum. This continuum is defined with respect to acoustic salience and frequency of occurrence across languages, such that robust contrasts are high in acoustic salience and occur frequently in the world's languages and fragile contrasts are low in acoustic salience and occur rarely across languages. Although databases exist to establish the latter values, no metric is available to quantify acoustic salience. According to Burnham, perceptual reorganization occurs at two points in development. The first reorganization occurs early in development, within the first year, and affects perception of fragile contrasts; the second reorganization occurs later, around 5–6 years of age, and may affect differentiation of robust non-native contrasts.

Clearly, developmental data on additional non-native contrasts are needed to better understand the basis for divergent patterns in cross-language phonetic perception. The present study was designed to address this need by examining the effects of age and language experience on the perception of a stop–fricative contrast, /d–ð/, by French- and English-speaking adults, and French- and English-learning infants. This contrast is phonemic in English but not in French, which has a dental voiced stop, /d/, but lacks either a /ɵ/ or /ð/ phoneme.

There is abundant anecdotal evidence supporting the claim that French Canadians typically substitute /d/ for /ð/ and /t/ for /ɵ/ when they attempt to produce the English interdental fricatives. Several studies also indicate that this production error is due, at least in part, to problems in perceptual differentiation of these phones (Jamieson and Morosan, 1986, 1989; Morosan and Jamieson, 1989; Werker *et al.*, 1992). These researchers report that French Canadian adults who are learning English perceive English /ð/ as an instance of French /d/ and English /ɵ/ as an instance of French /t/, and thus describing a single category assimilation pattern for English /d–ð/. To date, Morosan and Jamieson (1989) have reported the most detailed assessment of Francophone perception of this stop–fricative contrast. They examined the perception of /ð/ versus /d/ by Francophones in the context of a study designed to examine the effects of training on perception of English /ɵ–ð/ by Quebec French-speaking adults. They used both natural /d/ and /ð/ speech tokens and a synthesized /ð/ to /d/ continuum. Their results indicate that the Francophones had difficulty identifying the natural tokens correctly. In particular, Francophones had problems identifying the /ð/ items with the shortest frication durations, which suggests that they were relying only on the frication duration due to differentiate this contrast. Their identification of the /d–ð/ continuum also failed to show a clear categorization of the series.

In the present study, we examined perceptual differentiation of the English /d–ð/ contrast by English-speaking and Canadian French-speaking adults and English-learning and Canadian French-learning infants at 6–8 and 10–12 months of age using the conditioned headturn procedure. We expect to replicate the effects of age and language experience first reported by Werker and colleagues. Specifically, we expect performance to be poorer for French compared to English subjects for the adults and 10- to 12-month-olds but no difference to be evident for 6- to 8-month-olds. Thus, with respect to developmental patterns, we expected to find evidence of maintenance (i.e., no change with age) for the English group and developmental decline beginning at 10–12 months in the French group.

These results are predicted for three reasons. First, this outcome follows clearly from previous findings given that, in every study to date, when a language effect is evident in adult perception a decline in differentiation has been observed in the first year of life for infants from the non-native group. Second, as outlined above, previous adult studies indicate that Francophone adults assimilate English /d/ and /ð/ to a single category in their native language. Thus, perceptual decline during infancy is consistent with Best's PAM model. Third, English /d/ and /ð/ are short, low-amplitude phones, /ð/ is among the weakest sounds that occur in English (Fletcher, 1953; Ling and Ling, 1978), and the /d–ð/ contrast is also quite rare across languages of the world (Maddieson, 1984). According to Burnham, these facts define this contrast as fragile, and thus, perception of this contrast is expected to decline in the first year for non-native listeners.

II. METHODS

A. Stimuli

The stimuli consisted of two sets of naturally produced English minimal work pairs, /bot–vot/ (''boat''–''vote'') and /doz–ðoz/ (''doze''–''those''). The /b–v/ pair was selected as a control for task performance because it is present in both English and French and it contrasts the same manner classes and similar place differences as /d–ð/. Specifically, each contrast consists of a voiced stop versus a nonsibilant fricative with a small difference in place of articulation. It was considered important to use a comparable control contrast given previous findings suggesting that perception of fricatives may be more difficult for infants even in their native language (Eilers and Minifie, 1975; Eilers *et al.*, 1977; Holmberg *et al.*, 1977). Using this control, we could be confident that differences in performance with /d–ð/ can be attributed to effects of age or language experience over and above any effects of stimulus salience.

Multiple instances of boat, vote, doze, and those were recorded as produced in a short carrier phrase (''Number 1, those'') by a 26-year-old male monolingual native Canadian English speaker. These stimuli were digitized at a sampling rate of 10 kHz (12-bit resolution; low-pass filtered at 4.8 kHz) using a Macintosh IIfx computer with MACSPEECH software. Four /bot/, four /vot/, five /doz/, and five /ðoz/ tokens were selected so that the items within each contrast had matching values with respect to fundamental frequency, vowel amplitude, and five durational measures (prevoicing, total syllable, vowel, closure, and final burst/frication). this ensured that neither contrast could be differentiated by attending to extraneous acoustic differences that are not reliable cues to the phonetic contrast. In the final set, the /bot/ and /vot/ tokens had a mean duration of 325 ms (range=285.5–327.4 ms) and the /doz/ and /ðoz/ tokens had a mean duration of 443.4 ms (range=405.7–479.1 ms).

TABLE I. Acoustic cues distinguishing the initial consonants for the /bot–vot/ stimuli and /doz–ðoz/ stimuli. The * denotes a cue with completely nonoverlapping values; the + denotes a cue in which average values differ but there is some degree of overlap.

	Mean	Range	Mean	Range	Cue status	Difference between means
	/b/		/v/			
Noise duration (ms)	7.8	5.3–10.4	35.9	27.3–43	*	28.1
Noise amplitude (dB)	53.5	49.6–55.8	59	56.9–62.2	*	5.5
*F*2 at onset (Hz)	1172	1129–1210	1241	1210–1272	+	69
*F*2 change (Hz)	45.5	10–81	58.7	10–142		13.3
	/d/		/ð/			
Noise duration (ms)	16.2	7.7–20.4	18.6[a]	8.5–39.6[a]		2.4
Noise amplitude (dB)	53.7	50.1–56.7	56.2[a]	51.4–60[a]		2.5
*F*2 at onset (Hz)	1746	1699–1790	1536	1455–1699	+	210
*F*2 change (Hz)	604	550–681	456	336–631	+	148

[a]These values reflect only four of the five items because aperiodic noise energy could not be measured for one item.

The final stimulus set was redigitized to a 386 PC using BLISS (Mertus, 1990) and SWIFT software (sampling rate of 10 kHz, 12-bit resolution) to conduct adult and infant perceptual testing. Four monolingual English-speaking adults were asked to identify the initial consonant in each item and to comment on any unclear items. All four adults reported that all 18 items were clear, unambiguous examples of the intended words, confirming that the stimuli were high intelligible for native adults. These adult judgments were obtained in the same room and using the same setup, delivery system, and intensity level that was used in the infant and adult testing.

Acoustic analyses of the selected tokens were performed to identify the cues distinguishing each stop/nonsibilant fricative pair. As shown in Table I, these analyses included several measures of the initial aperiodic noise portion of each token as well as formant frequency measures. In this table, an asterisk (*) in the cue status column indicates that there were completely nonoverlapping distributions of the measure for the contrasting phones. These cues provide highly reliable information to distinguish the contrast. A plus (+) in this column denotes a measure for which there is a substantial difference in average values for the contrasting phones but some degree of overlap is present. Although these cues are less systematic they may also be useful in distinguishing the contrast. Measures with no asterisk or plus are similar across the contrasting phones and provided little or no information to help distinguish the contrast.

The duration of the initial aperiodic noise (i.e., stop burst or fricative energy) was measured by simultaneously referring to waveform and spectrographic displays. The average amplitude of the initial noise portion of the syllable was measured for the segment beginning at the onset of any prevoicing to the onset of periodicity of the vowel. For the /b–v/ contrast, the initial noise segment was shorter and less intense for /b/ than /v/ and there was no overlap of values for either measure. For /d–ð/, the duration and average amplitude of the initial noise segment differed only slightly between the /d/ and /ð/ items and there was considerable overlap in both values.[3]

Formant frequencies were measured for each item using MACSPEECH LAB II software via an LPC algorithm (13 poles) using the procedure described in Polka (1995). A 24-ms Hamming window was centered at successive 12.5-ms locations within each syllable, and measures were taken at the onset of voicing until voicing offset. Table I contains formant frequency measures corresponding to *F*2 at the onset of voicing and the *F*2 frequency change. The latter measure was defined as the extent of *F*2 frequency change between the onset and midpoint of the syllable, that is, during the initial *F*2 formant transition. The midpoint measure was taken at 50 ms from the onset for /bot/ and /vot/ tokens and at 137.5 ms from the onset for /doz/ and /ðoz/ tokens. These locations correspond to a point within each syllable which is close to where *F*2 reaches a frequency maximum for /bot/ and /vot/ tokens and to where *F*2 reaches a frequency minimum for /doz/ and /ðoz/ tokens.

As expected, given the place differences in these contrast, we found that on average the *F*2 onset frequencies were higher for /v/ than for /b/ and were considerably higher for /d/ than for /ð/ (Fant, 1970). For /b–v/, the mean *F*2 difference was small and there was one pair of /b/ and /v/ items with identical values. For /d–ð/, the mean difference was much larger than for /b–v/ and again there was one pair of /d/ and /ð/ stimuli with the same value. Given the manner differences in these contrasts, we expected to find evidence for more rapid *F*2 transitions for the stops relative to the fricatives (Pickett, 1999). Because our measures of *F*2 changes are computed over the same syllable durations, a greater *F*2 change indicates more rapid *F*2 change. For /b–v/ there was no clear difference or trend in the extent of *F*2 formant change. With respect to the /d–ð/ contrast, *F*2 change showed a clear tendency to be larger for /d/ than for /ð/, but there was some overlap in values for /d/ and /ð/ tokens. Thus, overall, for /bot/–/vot/, there are clear differences in aperiodic noise whereas *F*2 differences are present but less systematic. In comparison, for /doz/–/ðoz/, aperiodic noise cues are absent whereas *F*2 cues are prominent.

B. Subjects

Twenty-nine adults (19 females, 10 males) and 42 healthy, full-term infants (21 females, 21 males) served as subjects. The adult subjects included 15 monolingual French speakers (mean=24, range 19 to 35 years) and 14 monolingual English speakers (mean=21, range=18 to 28 years). Two additional adults, one French speaker and one English speaker, were excluded as they failed to meet the criterion (described below) with the /b–v/ control contrast. All adults reported having normal hearing and were paid for their participation. The English adults had resided in the province of Quebec for less than 4 years, and had only classroom instruction in French at the introductory level. None of the English adults listened to French radio or TV and none could speak a second language fluently. Francophone subjects were native speakers of Canadian French and had no more than basic high school English instruction. All Francophone adults resided in Quebec most of their lives. Some of the Francophone adults occasionally listened to English radio or TV but none was a fluent speaker of a second language.

The infant sample included 23 babies between 6 and 8 months of age: 10 French-learning (mean=7:15, range=6:02 to 8:16) and 13 English-learning infants (mean=7:04, range =6:00 to 8:10); and 19 babies between 10 and 13 months of age: 9 French-learning (mean=10:24, range 10:00 to 11:25) and 10 English-learning infants (mean=10:07, range=10:00 to 10:25). To get 42 infant subjects to complete the entire procedure, an additional 68 babies (32 English; 34 French) were tested but their data were excluded for the following reasons: failed to meet criterion with /b–v/ on day 1 ($n=37$);[4] fussed during testing ($n=7$); failed to meet retest criterion on day 2 [described below] ($n=9$); unable to return for second test session ($n=10$); technical problems or experimenter error ($n=5$). Parents reported that infants had normal hearing and none had been treated for an ear infection in the month prior to the study. Parents were provided with two small gifts as tokens of our appreciation.

Language experience of each infant was assessed via parent interview. For the English infants, English was the native language of both parents; however, for five infants one or both of the parents were bilingual.[5] However, in every case both parents had learned English very early in life, spoke it fluently, and preferred to speak English. The language used by the parents and directed to the baby was English; other relatives, caregivers, and visitors interacted with the baby in English. For each of these infants, the language in the home with respect to TV and radio was English.

For the French infants, Canadian French was the native tongue of both parents except for one infant, whose mother's native language was Romanian, a language which does not contain interdental fricatives. Some of the parents could also speak some English but all of them preferred to speak in French. Thus, for every infant in the French group the language used by the parents and directed to the baby was French. Other relatives, caregivers, and visitors also interacted with the baby in French. The language in the home with respect to TV and radio was predominantly French but including some English for 8 of the 19 French infants.

C. Procedure

Infants were tested in the headturn procedure using the protocol described in Polka and Werker (1994). In this procedure a syllable is played from a loudspeaker every 1500 ms and at random intervals this background syllable changes to a target syllable for a brief interval. Testing began by first conditioning the infant to turn his/her head toward a visual reinforcer when a change in the background syllable occurred. Correct headturns are reinforced by the activation of a visual reinforcer (an electromechanical animal that moves) and the verbal praise of an assistant. We implemented this procedure as a category change paradigm in which the background and the target consist of multiple tokens of each syllable type.

Perception of each stop/fricative contrast was tested in a single session. The infant was seated on the parent's lap across a small table from an experimenter (E1). The loudspeaker and an array of four visual reinforcers, located behind a smoked Plexiglas panel, were located to the left of the parent and infant. Both the parent and E1 listened to vocal music over headphones to prevent them from influencing the infant's behavior. A second experimenter (E2) located outside the test room observed the infant through a one-way window and operated the computer.

The session began with a conditioning stage in which the infant was given an opportunity to learn the contingency between the consonant change and the visual reinforcer. Only a single exemplar of each syllable type was used in the conditioning stage. Once the infant had made at least three consecutive correct anticipatory headturns, the testing stage began. Conditioning continued up to a maximum of 20 trials. During the testing stage multiple tokens of each syllable type were presented as the background and target stimuli. Also, both change and control (no-change) trials were presented according to a semirandom schedule in which no more than three consecutive control or change trials could occur. In the testing stage, E2 initiated trials when the infant was in a ''state of readiness'' (facing E1, not fussing, etc.). E2 was blind to the trial type and pushed a button when she observed a headturn during the trial interval. The visual reinforcer was activated automatically on a change trial when E2 recorded a headturn within a 4.5-s window; three syllables are presented during this interval. A retraining protocol was also implemented during the test stage to provide up to six retraining trials (change trials that are automatically reinforced if no headturn occurs). Performance on retraining trials was excluded from all data analyses. Twenty-five trials were presented during the testing stage; approximately 55 percent of the test trials were change trials and 45 percent were control trials.[6]

Infant testing was conducted in a sound-treated chamber. The stimuli presentation was controlled on-line from an IBM format computer via a data Translation DT2801 D/A board and stimuli were routed through a Yamaha AX-350 amplifier for delivery at an intensity of 68 dBA (at approximate ear level of the baby) via a Cyrus 780 loudspeaker. Computer software controlled the stimulus delivery, activation of the reinforcers, and trial selection, and recorded hits, misses, correct rejections, and false alarms.

Adult subjects were tested using the same basic procedure as the infants. Each adult was seated in the same chair as the parents had used and was read a short set of instructions that instructed them to raise their hand after hearing a sound change. The reinforcers were activated just as with the infants. Thus, adults experienced the same masking effects created by the noise (if any) and also received feedback for their correct responses. In the conditioning stage, adults were given a minimum of three and a maximum of six conditioning trials. In testing only 25 test trials were presented; no retraining trials were presented.

D. Design

Each subject was tested on both contrasts. With the infants, testing was completed in two sessions conducted on different days, with /bot/–/vot/ on day 1 and /doz/–/ðoz/ on day 2. Infant pilot testing with /bot/–/vot/ revealed that differentiation was more difficult when /bot/ was the background than when /vot/ was played as the background. Following this, it was decided that all infants would be tested with /vot/ as the background (and /bot/ as the target). This would allow a greater number of babies to succeed in the control condition and would also prevent differences in performance with the control condition from influencing performance in the test condition. Only infants who met a minimum criterion of eight out of ten consecutive correct responses in the testing phase on day 1 were invited to continue the experiment on day 2.

On day 2, infants were tested on the /doz/–/ðoz/ contrast. For this condition, the direction was counterbalanced between subjects such that half were tested with /doz/ as the background stimulus and half were tested for /ðoz/ as the background. If a minimum criterion of 8/10 correct was not met on day 2, a retest was immediately implemented using the /vot/–/bot/ stimuli from day 1. The retesting was conducted until the 8/10 minimum criterion had been met or a maximum of 15 test trials was administered. The retest was conducted to determine whether the infant was still on task and thus to assess whether poor performance was due specifically to difficulty differentiating the test stimuli or due to general inattentiveness and/or fatigue.

The adult test protocol differed from that of the infants in three ways. First, French- and English-speaking adults were tested in a single session in which both stimulus pairs were tested: /vot/–/bot/ followed by /doz/–/ðoz/. Second, the direction of change was counterbalanced across subjects for both contrasts. Finally, adults were not given a retest following poor performance on /doz/–/ðoz/.

III. RESULTS

Data obtained from 42 babies were included in our analyses. Each of these babies provided evidence that she/he could perform the headturn procedure by meeting one or two criteria. To meet criterion one, the infant had to respond correctly on eight out of ten consecutive trials on /b–v/ on day 1 and either on /d–ð/ or on the /b–v/ retest on day 2. Thirty-three babies met this criterion. Infants were also included if they met a second criterion. A second criterion was

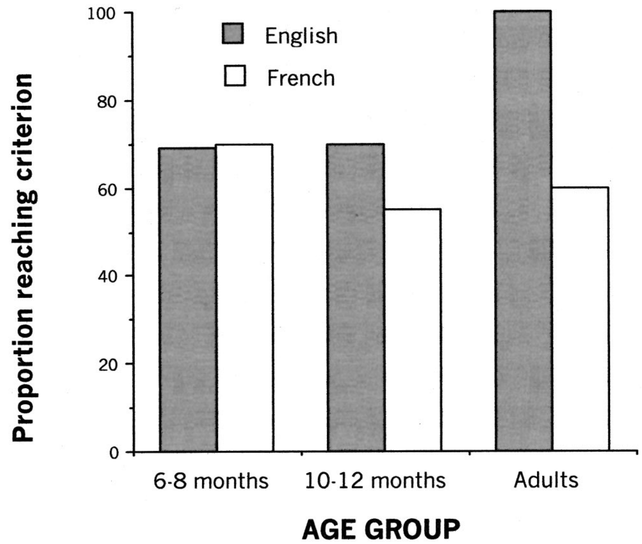

FIG. 1. Proportion of subjects reaching criterion on differentiation of /d–ð/ in each age and language group.

defined because we found that very few infants could complete the /b–v/ retest. These data and our observations indicated that presenting the retest immediately following the /d–ð/ test was too taxing for many infants. To meet criterion 2, the infant had to respond correctly on seven out of eight consecutive trials and show an overall accuracy greater than 60% on day 1. Thus, these infants could fall below the 8/10 criterion on both /d–ð/ and the /b–v/ retest on day 2, but they were required to show a higher level of performance on day 1 compared to criterion 1 infants.[7] Nine infants met criterion 2; five French infants (two 6- to 8-month-olds; three 10- to 12-month-olds) and four English infants (three 6- to 8-month-olds; one 10- to 12-month-old). Each analysis was repeated with criterion 2 babies removed from the sample and in every case the pattern of results obtained was identical.

The proportion of subjects reaching an 8/10 criterion on /d–ð/ is shown for each age and language group in Fig. 1. Over 55% of the subjects in every group reached this criterion. Chi-squares were conducted to determine whether the proportion of subjects reaching criterion in each group was different for those subjects tested on a /d/ to /ð/ change versus those tested on a /ð/ to /d/ change. No direction effects were evident in any of the groups; thus, all subsequent analyses were conducted on proportions collapsed across direction of change. Chi-squares were computed to assess the effect of language in each age group. The results showed that significantly more adults reached the criterion in the English group than in the French group, $X^2=6.64$, $p<0.01$. The proportion of French and English infants reaching criterion did not differ for either the 6- to 8-month-olds or the 10- to 12-month-olds. Separate analyses of proportions (ANPROs) as described by Marascuilo (1966) were conduced for each language group to analyze effects of age (6–8 months versus 10–12 months versus adults). The ANPRO analyses failed to reach significance for either language group. Thus, there were no age differences in either language group with respect to the proportion of individual subjects reaching criterion.

To analyze for more subtle effects of age and language

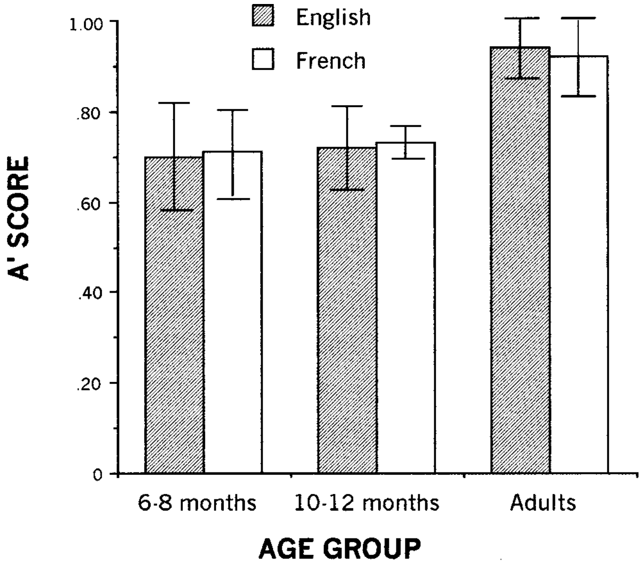

FIG. 2. Mean A-prime scores on differentiation of /b–v/ in each age and language group. Error bars show +1 to −1 SD.

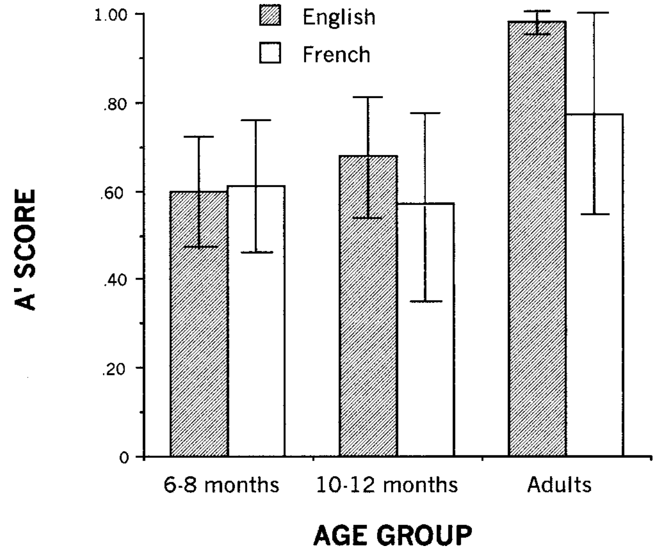

FIG. 3. Mean A-prime scores on differentiation of /d–ð/ in each age and language group. Error bars show +1 to −1 SD.

experience on perceptual performance, we computed A-prime scores for each subject on each contrast.[8] A-prime is a nonparametric index of sensitivity (similar to d-prime), which ranges from 0 to 1 (with 1 being a perfect score, 0.5 representing chance). The A-prime scores reflect each individual subject's hit rate corrected for their rate of false alams (Grier, 1971).[9] Mean A-prime values are plotted for differentiation of the /b–v/ and /d–ð/ contrasts in Figs. 2 and 3, respectively; error bars show the range corresponding to plus and minus 1 standard deviation. For the /b–v/ contrast (Fig. 2), the mean A-prime scores for the English and the French groups are almost identical at each age. For /b–v/, the variability in performance is similar for French and English subjects in the 6–8 month group and in the adult group, whereas the older French infants show less variability compared to the older English infants. To assess whether there were differences among the groups on differentiation of the /b–v/ control contrast, the A-prime scores were submitted to a two-way age (6–8 months, 10–12 months, adults) by language (English, French) analysis of variance (ANOVA). As expected, the main effect of language and the age by language interaction failed to reach significance. There was a main effect of age $[F(2,59)=29.36,\ p<0.01]$. Subsequent Tukey pairwise comparisons $(p<0.01)$ showed that the adults performed better than both infant groups, but the two infant groups did not differ.

For the /d–ð/ contrast (Fig. 3), A-prime scores show divergent patterns of performance across the two language groups. For the English subjects, mean A-prime scores increase with age with a very large increase between infants and adults. For the French subjects, mean A-prime scores for the 6- to 8-month-olds and the 10- to 12-month-olds are almost identical, whereas A-prime scores for the French adults are higher. With age, intersubject variability increased for the French subjects and decreased for the English subjects. Intersubject variability is similar for French and English subjects at 6–8 months, whereas at 10–12 months and in the adults intersubject variability is clearly higher in the French group compared to the English group. The A-prime scores on the /d–ð/ contrast were analyzed in a three-way age (6–8 months, 10–12 months, adults) by language (English, French) by direction (d to ð; ð to d) ANOVA. Neither the main effect of direction nor any interactions of direction with the other factors were significant. As expected, the main effect of language $[F(1,59)=6.85,\ p<0.01]$ was significant, showing that overall the English subjects performed better than the French subjects. The main effect of age was also significant $[F(2,59)=18.90,\ p<0.01]$. Subsequent Tukey pairwise comparisons $(p<0.01)$ revealed that the adults did significantly better than both groups of infants, whereas the infant groups did not differ from each other. The only interaction to approach significance was age by language $[F(2,59)=2.72,\ p<0.07]$.[10] Simple effects analyses were conducted to probe the age by language interaction. The effect of language was significant only for the adults $[F(1,59)=13,\ p<0.01]$, consistent with the ANPRO results. The effect of age was significant for the English subjects $[F(2,34)=47.29,\ p<0.0001]$, but not for the French subjects. Subsequent Tukey pairwise comparisons showed that the English adults performed better than both infant groups $(p<0.01)$ but there was no significant difference between the two infant groups.[11]

IV. DISCUSSION

The present experiment provided a cross-language comparison of perceptual differentiation of the stop–fricative contrast /d–ð/ by English- and French-learning infants, and English- and French-speaking adults. Overall, the findings were inconsistent with our predictions regarding language effects and development patterns. With respect to language effects, we observed a robust effect of language experience in the adults, as expected. French adults were consistently less accurate and showed greater intersubject variability compared to English adults. With respect to the 6- to 8-month-olds, there was no evidence of a language effect in any of our analyses, also as expected. However, contrary to our predictions, the 10- to 12-month-olds failed to show an effect of language experience. At this age, English and French infants did not differ either in the proportion reaching a preset criterion or in A-prime scores. There was only one subtle sign of any difference in the older infants, i.e., intersubject variability was observed to be higher in the older French infants compared to the older English infants. Thus, a robust effect of language experience was observed in adults but not in infants.

With respect to developmental patterns, the English and French listeners differed, but the specific development patterns did not match our predictions. For English listeners, comparable performance levels were maintained across both infant ages, whereas there was clear evidence of an increase in performance between 10–12 months and adulthood. This developmental pattern is statistically supported in analysis of A-prime scores and there is a clear trend towards the same pattern in the proportion of infants reaching a preset criterion. These results indicate that for native listeners, perceptual differentiation of /d–ð/ improves with increasing age and language experience after 12 months of age.

For French listeners, there were no significant changes in differentiation of the /d–ð/ with increasing age. No age effects were found in analyses of A-prime scores, or proportion reaching criterion. Greater intersubject variability was noted in the French adults and the older French infants compared to the younger French infants. These findings suggest that, for French listeners, the level of perceptual differentiation observed in infancy is maintained across development.

It is important to note that analysis of A-prime scores for the /b–v/ contrast showed the same pattern of age differences (adults $>$6–8$=$10–12) for both English and French subjects. This finding further confirms that the divergent patterns observed in French and English subjects' differentiation of /d–ð/ are attributable to differences in language experience.

Overall, our data fail to confirm our initial predictions regarding effects of age and language experience. Instead, two new findings emerged in the present study. First, perceptual differentiation of /d–ð/ in the headturn paradigm appears to be unaffected by language experience in the first year of life, even though very clear language effects are evident in adults. Second, it appears after 12 months of age language experience has a facilitative effect on perception of this contrast, in that significant age-related increase in differentiation of /d–ð/ is evident in the English groups but no change is evident in the French groups.

How do we explain our finding that perceptual differentiation of this contrast does not appear to be strongly affected by language experience within the first year of life? We have identified several plausible explanations; they are not mutually exclusive. First, within the framework provided by PAM (Best, 1995), it is conceivable that effects of language experience for this contrast are subtle because of the way in which this contrast relates to the phonology of French. Recall that previous studies have consistently shown language effects at 10 to 12 months of age for contrasts that fit the SC assimilation pattern for non-native adults and that earlier findings describe Francophone perception of English /d–ð/ as fitting this pattern. The high variability in performance of our French adults led us to question the latter conclusion. Therefore, we also gathered some data on assimilation of this contrast from the last six French adults that we tested using procedures outlines by Best (Best *et al.*, 1996) for making such assessments.[12] Four different assimilation patterns were supported in these data. One subject's data were consistent with a two-category (TC) pattern in that he identified English /d/ and /ð/ as good matches to ''d'' and ''th,'' respectively. Three of the subjects selected ''d'' to label both /d/ and /ð/; one of these subjects showed a single-category (SC) pattern and the other two subjects supported a category-goodness (CG) pattern. The two remaining subjects did not fit a clear assimilation pattern in that they selected both ''d'' and ''th'' to identify each phone.[13] Overall, this effort revealed that most French adults confuse /d/ and /ð/ to varying degrees, whereas a small subset of French adults perceived English /d/ as similar to French /d/ and recognized English /ð/ as being a non-native phone.[14] The order of performance among these six subjects also appears predictable from their assimilation data, with the TC subject showing the best performance, the two confused subjects and the SC subject doing the poorest, and the two CG subjects falling in between. Thus, the high intersubject variability in the French adults' performance is consistent with the observed differences in assimilation pattern. Given these findings, perhaps the greater intersubject variability found in the older French infants relative to the older English infants is indeed tied to differences in language experience.

It is also possible that the absence of clear language effects for this contrast at 10–12 months is due—at least in part—to the acoustic properties of these contrasting phones. As mentioned earlier, /d/ and /ð/ are short, low-amplitude phones (Pickett, 1999) and /ð/ has been reported to be among the weakest phones present in English (Fletcher, 1953; Ling and Ling, 1978). Thus, it could be that it is more difficult for infants to attend to such acoustically weak units. In fact, several earlier studies have suggested that infants have greater difficulty differentiating contrasts involving nonsibilant fricatives even in their native language (Eilers and Minifie, 1975; Eilers *et al.*, 1977; Holmberg *et al.*, 1977). Two aspects of our data further support this claim. First, our attrition due to inability to meet criterion with the /b–v/ control contrast was quite high in each infant group. Second, we found that 70 percent of the infants in each group were able to meet our criterion on /d–ð/. In comparison, successful differentiation has been observed in 80 to 90 percent of 6- to 8-month-olds tested on other consonant contrasts in studies using the same procedure and similar or even higher criteria (e.g., Werker *et al.*, 1981; Werker and Tees, 1984a).

Recall that Burnham (1986) has claimed that language effects emerge earlier in development (during the first year) for contrasts that meet two criteria that form the definition of a fragile contrast, i.e., low acoustic salience and rare occurrence among languages of the world. Given that the /d–ð/

contrast clearly fits this definition, our findings are clearly inconsistent with the hypothesis. Indeed, our findings appear to suggest the opposite—that fragile contrasts remain unaffected by language experience in the first year of life. Perhaps acoustically weak contrasts are less vulnerable to perceptual decline when relevant language experience is lacking because, although they can, infants do not readily attend to such differences. If so, then contrary to Burnham's proposal, an acoustically weak contrast appears to delay rather than to promote the onset of language specific tuning.

The unique phonotactic properties of English /ð/ may also contribute to the absence of language effects during infancy. The phoneme /ð/ occurs with a very high frequency in initial position in spoken English, but only in function words (Morgan, Shi, and Allopenna, 1996). Function words are less salient forms in natural discourse given that they are short, contain unstressed vowels, are typically not produced in isolation, and are not highlighted by intonation (Morgan, Shi, and Allopenna, 1996). Recent findings show that newborns are sensitive to the correlated acoustic and phonological properties that distinguish content and function words (Shi, Werker, and Morgan, 1999). Moreover, at 6 months of age infants prefer to listen to content words over function words, thus showing that infants are paying more attention to content words than function words (Shi and Werker, 2001). Accordingly, recognition of phonetic elements that appear exclusively in function words, such as /ð/, may not occur until infants begin to focus their attention on this class of syntactic elements.

An interesting connectionist model recently proposed by Behnke (1998) allows for both of the latter two possibilities to explain why language effects emerge later in development for some phonetic contrasts than for others. According to Behnke, delays may occur either because general limitations in auditory processing during infancy make it difficult for infants to differentiate certain phonetic contrasts (e.g., contrasts involving brief or low-amplitude phones) and/or because differentiation of some contrasts may remain difficult until the child has gained lexical knowledge that serves to fine-tune phonetic processing.

A fourth plausible account for the lack of language effect in our infants is that we may not have selected the right level of analysis to isolate language effects in perception of this contrast. In this study, we described language differences with respect to the presence versus absence of specific phones in French versus English. There are considerable data to support an approach in which language-specific processing is described in terms of the perceptual weighting of the acoustic cues underlying a given contrast (Harnsberger, 1999). Thus, to isolate effects of language experience, it may be more meaningful to consider the multiple cues underlying this stop–fricative contrast and the relative salience of each for French and English listeners. Morosan and Jamieson (1989) suggest that French and English adults differ in perceptual weighting of cues to the /d–ð/ contrast. Their perceptual data suggest that French adults rely on frication duration to identify /ð/. Thus, differences in cue weighting may contribute to the poorer performance and greater variability in older French infants and French adults and the varied assimilation patterns for the latter. The use of natural speech in this study does not allow us to isolate such differences. Further research using synthetic stimuli is needed to investigate the relationships between age, language experience, cue salience, and assimilation patterns.

The second finding in this study concerns the differences between infants and adults. Previous developmental cross-language studies generally support a maintenance view of language experience. In the maintenance view, specific language experience serves to prevent a developmental decline in perceptual differentiation for some contrasts. However, our data indicate that language experience serves to facilitate perception of /d–ð/ after 12 months of age; in the absence of language experience, adult performance is still comparable to the level observed in infancy. It should be noted that adults have been shown to perform better than infants in several previous cross-language studies (e.g., Polka and Werker, 1994; Polka and Bohn, 1996; Best *et al.*, 1990). However, these differences have been observed either only within non-native listeners or within both native and non-native listeners and thus indicate more general age-related changes. The differences in perceptual differentiation observed between English infants and adults in the present study most likely reflect some general age-related differences in task performance between these two age groups. However, given that the comparison of French adults and infants fails to reveal comparable improvement indicates that some of the age effects in the English group are attributable to a facilitative effect of language experience.

It is worth considering why a maintenance view has found clear support in the previous research while evidence in support of facilitation is lacking. There are at least two reasons. First, previous studies supporting a maintenance view have typically examined dichotomous measures of perceptual performance, such as a preset criterion or presence/absence of release from habituation, and thus have not always considered more subtle quantitative differences in performance. Second, they have typically not included a complete control group of native listeners at each age to compare with the non-native listeners. With the opportunity to compare both native and non-native subjects in each age group, the interpretation of continuous measures of perceptual accuracy becomes more meaningful. Thus, our data elaborate rather than challenge previous findings because the design used here permits us to bring more information to the interpretation of developmental patterns.

Although a facilitative effect of language experience on phonetic differentiation has not been clearly demonstrated in any previous developmental cross-language study, this finding is not surprising. None of the current models of phonetic development claim that phonetic perception is adult-like in a 1-year-old. Moreover, a facilitative role of language experience is entirely consistent with the literature on development of phonemic perception. Studies of phonemic perception in children learning English show that accuracy in phoneme perception improves during the preschool years such that perception of most native phonemic contrasts becomes adult-like between 2 and 10 years of age (Templin, 1957; Barton, 1980; Luksaneeyanawin *et al.*, 1997). A great deal of research has focused on early infancy, yet there is much to be learned about the role of language experience in phonetic development during childhood. Werker and Tees (1983) reported that 4-, 8-, and 12-year-olds, as well as adults, had difficulty differentiating two Hindi contrasts that were difficult for 10- to 12-month-olds and adults. For the Hindi voicing contrast, none of the 4-year-olds they tested was able to reach criterion, whereas about half of the older children and adults did. Burnham (1986) has reported similar findings showing a dip in identification of a non-native voicing contrast at 6 years followed by some recovery in performance in older children and adults. It is not clear what factors contribute to these later changes in phonetic perception. Werker and Tees (1983) suggest that the rigid processing strategies often displayed by 4-year-olds may make it especially difficult for them to attend to nonphonemic differences. Burnham has proposed that a decline at 6 years occurs as a result of increased attention to phonemic structure typically encouraged at the onset of formal education (Burnham *et al.*, 1991; Burnham, 1986).

Our finding that perceptual differentiation did not change in the absence of language experience was more surprising. In all previous studies, clear language effects in adults have been associated with a decline in perceptual differentiation at an earlier point in development. It is possible that differentiation of this contrast does decline at a later point in development and then eventually recovers to the level observed in infancy.[15] Research underway in our lab will address this issue. Nevertheless, the present pattern of results suggests that when differentiation of a contrast is difficult in infancy there is no further development decline, whereas relevant language experience can act to boost this initial level of perception. For such contrasts advances in linguistic processing may be essential to fine-tune phonetic perception to levels observed in mature native listeners. Accordingly, for such contrasts robust language effects may not be evident until such linguistic maturity has been achieved. In this case, such contrasts may be especially useful to investigate the influence of language processing in the development of phonetic perception.

In summary, the present study has shown that perceptual differentiation of /d–ð/ is not influenced by language experience in the first year of life, but is clearly affected by language experience by adulthood. Further research is needed to determine whether this pattern of age and language effects is observed in other test paradigms or for other phonetic contrasts. Our future research will also aim to establish when facilitation effects emerge in perception of the /d–ð/ contrast, to determine whether a decline in Francophone perception is evident at this point in development, and to identify factors that contribute to the facilitative effect observed for this contrast.

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[1]Speech perception tasks used with infants generally do not assess the limits of their sensory capacities. For this reason we use the term differentiation throughout this paper in an effort to be clear that the perceptual measures of interest are not to be equated with sensory capacity but also reflect task-specific demands on memory, attention, and motivation.

[2]A different dialect of German was used in this study than in Polka and Werker (1994) reported above; see Polka and Bohn (1996) for further discussion of the discrepant results in these two studies.

[3]Comparisons of several different spectral representations of the initial aperiodic noise segments failed to reveal differences for either contrast.

[4]Attrition due to poor performance on the /b–v/ control contrast was similar across the infant groups; English 6- to 8-month-olds=34%, French 6- to 8-month-olds=38%, English 10- to 12-month-olds=37%, and French 10- to 12-month-olds=23%.

[5]For four of these infants the fathers also spoke Armenian, French, Ukranian, or Italian; for one infant the mother also spoke Italian, and for one infant both parents also spoke Italian.

[6]Five additional trials were presented if the infant was within 2 trials of reaching the 8/10 criterion. A slightly higher proportion of change trials is often used with infants to ensure sufficient reinforcement to sustain task performance.

[7]Some debate surrounds the calculation of probability of attaining a preset criterion in the headturn procedure. However, regardless of calculation method used, p levels are always lower for 7/8 (87.5%) than for 8/10 (80%) for a 25-trial sample, probability estimate for both criteria is at least 0.05. Six of the nine infants meeting criterion 2 got 9/10 correct on day 1; the estimated probability for this criterion is at least 0.01.

[8]Every analysis of A-prime scores reported here was repeated using percent correct as the dependent variable and produced the same pattern of results.

[9]The formula used was

$$A' = 0.5 + (H - FA)(1 + H - FA)/[4H(1 - FA)],$$

where H=proportion of hits and FA=proportion of false alarms.

[10]In the analysis of percent correct scores this interaction was highly significant [$F(2,59) = 6.84$, $p < 0.005$].

[11]A language by age by contrast ANOVA including both contrasts revealed a main effect for contrast and a language by contrast interaction. Simple effect analysis of contrasts revealed that French subjects performed worse on /d–ð/ than on /b–v/ whereas performance on the two contrasts did not differ for English subjects. Simple effects of analysis of language also showed that language effects were evident for /d–ð/ but not for /b–v/.

[12]Following the headturn task, these subjects were asked to identify the initial consonant in each doze, those, boat, and vote syllable using a closed response set (b, p, d, t, th, v, or other) and then to immediately rate how well the item matched their selection on a scale of 1 (very poor match) to 5 (very good match). We included ''th'' as a response alternative because Francophone adults are generally aware that English contains this problematic ''th'' sound.

[13]This outcome most likely reflects an unsuccessful attempt to guess when they are hearing ''th.''

[14]With the closed-set identification task used we cannot be sure that French adults can accurately label English /ð/ or simply chose the ''th'' response instead of ''other'' (which was never chosen) when they were not sure what sound they heard.

[15]It may be that the Francophone adults' minimal exposure to English is relevant to a possible recovery. Of interest in this respect, we noted that differences in amount of exposure to English among the Francophone adults (measured via a questionnaire) appear to be unrelated to /d–ð/ differentiation accuracy.

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