The Effect of Spectral Tilt on Infants' Speech Perception: Implications for Infants with Hearing Loss

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A thesis submitted
for the degree of
Doctor of Philosophy

MARCS Auditory Laboratories
University of Western Sydney
August, 2009

Acknowledgements

First, I would like to thank my supervisor, Dr Christine Kitamura, for giving me the opportunity to undertake this project[1]. I am grateful to Chris for her encouragement, friendship, and wisdom, and for steadfastly refusing to accept anything less than my best effort.

I would also like to thank Professor Denis Burnham, who facilitated my return to academic endeavour after a long break and provided me with an opportunity that I thought had surely passed me by.

Thank you to all those I have had contact with at the National Acoustic Laboratories and Australian Hearing, particularly Drs Harvey Dillon and Teresa Ching, who provided specialist advice and assistance on many aspects of the project.

Thanks to everyone at MARCS, who, together, create such a fabulous collegiate atmosphere. Special thanks to students and staff of the BabyLab – Prof Cathi Best, Dr Michael Tyler, Christa Lam, Anna Notley, Suzy Bicanic and Cat Grimsgaard; and most importantly, thank you to all the babies and their parents who participated in these studies.

I am especially grateful to Caroline and Jordan Hill for giving me such an intimate insight into the practical and emotional aspects of dealing with hearing loss in infancy.

Special thanks to my family, especially Mum and Dad, and Jeff and Sandra, for supporting me and caring for my children on countless occasions.

Finally, heartfelt thanks to Matt, Jacqueline and Genevieve for believing in me, loving me, supporting me (in so many ways) and giving me the space and time I needed to get the job done.

[1] funded by Australian Research Council grant DP 0559134.

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ABBREVIATIONS

ABR	auditory brain stem response
ADS	adult-directed speech
BOA	behavioural observation audiometry
CHT	conditioned head turn
DSL	Desired Sensation Level
EEG	electroencephalogram
ERP	event-related potentials
IDS	infant-directed speech
HI	hearing impaired
HL	hearing loss
LLI	language-learning impairment
LTASS	long-term average speech spectrum
MMN	mismatch negativity
NAL-NL1	National Acoustic Laboratories – Nonlinear Version 1
NFC	nonlinear frequency compression
NH	normal hearing
NLM	Native Language Magnet
NLM-e	Native Language Magnet-expanded
NSW	New South Wales
OAE	otoacoustic emissions
PAM	Perceptual Assimilation Model
PDS	pet-directed speech
RECD	real-ear-to-coupler difference
SA	South Australia
SPL	sound pressure level
VH	visual habituation
VOT	voice onset time
VROA	visually reinforced orientation audiometry
WA	Western Australia

ABSTRACT

Infants with hearing loss (HL) are being diagnosed and fitted with amplification earlier than ever before. In order to acquire speech and language abilities that are on par with their normal-hearing (NH) peers, hearing-impaired (HI) infants require amplification that provides appropriate exposure to the sounds of their native language. To date, no research has addressed this issue and thus, there is a need to examine the type of amplification that is most suitable for infants during the early stages of language acquisition. In this thesis, three different amplification types were compared: one that preserves the natural spectral shape of speech (unmodified speech); a second that emphasises high-frequency speech information (positive spectral tilt); and a third that emphasises low-frequency information (negative spectral tilt). NH infants were tested to examine how each of these amplification types affects speech perception and to explore whether infants at different stages of language acquisition find modified spectral tilt a help or hindrance in perceiving native-language speech contrasts.

A visual habituation (VH) procedure was used to test 288 6- and 9-month-old NH infants on their ability to discriminate the high-frequency fricative contrast /f/-/s/; the mid-frequency approximant contrast /l/-/r/; and the low-frequency vowel contrast /ɐ/-/ɔ/ under modified spectral tilt conditions. For each speech contrast, 96 infants were tested in one of three conditions: (a) unmodified spectral tilt (n = 32); (b) with a positive 6 dB/octave spectral tilt (n = 32); or (c) with a negative 6 dB/octave spectral tilt (n = 32).

The results showed that both 6- and 9-month-olds discriminated the three speech contrasts in the unmodified condition. However, when the contrasts were spectrally modified, a consistent developmental trend emerged. Six-month-olds' discrimination performance improved when the spectral tilt modification amplified the relevant frequency information. That is, for the consonant contrasts (fricatives /f/-/s/ and approximants /l/-/r/) 6-month-olds performed best when high-frequency information was emphasised, whereas for the vowel contrast (/ɐ/-/ɔ/) the best

discrimination performance was found when low-frequency information was enhanced. Nine-month-olds, on the other hand, showed no evidence of discriminating any of the contrasts when spectral tilt was modified. For all three contrasts, the older infants' best discrimination performance was in the unmodified spectral tilt condition.

The findings reflect the early stages of linguistic development. Six-month-olds, whose acoustically driven speech perception operates in a language-general mode, demonstrated a broad-based ability to discriminate speech sounds. They not only accommodated speech with positive or negative spectral tilt, but a facilitation effect was observed when relevant frequency information was amplified. In contrast, 9-month-olds, whose perception is linguistically driven, found that spectral tilt modifications hinder speech perception. It seems that because older infants are attuning to native phonemic categories, their attention is constrained to native-language spectral profiles only. Thus, even those spectral tilt modifications that should have been beneficial for perception were eschewed by 9-month-olds because they were incompatible with the older infants' narrow focus on spectrally intact native speech sounds.

Only NH infants were tested in this study, so it is not possible draw firm conclusions about amplification schemes until HI infants are tested too. Nevertheless, the results have a number of implications for infants with HL. The demonstration that spectral tilt modifications interfere with older NH infants' speech perception suggests that future research should investigate whether HI infants also show this developmental pattern. That is, do HI infants progressively attune to the native language, and if so, does this affect their perception of spectrally modified speech sounds? Moreover, if HI infants are to attune to the native language and acquire speech and language in the same way as their NH peers, then the research reported here suggests that, throughout infancy, HI infants will need access to amplified speech that maintains the spectral shape of natural speech.

Thus, the current research demonstrates, for the first time, a developmental difference in the way that infants perceive spectrally modified speech, one that is closely linked to the infant's stage of native-language attunement. This research provides a solid foundation on which to conduct further research with HI infants and offers preliminary suggestions with regard to amplification and intervention to ensure that HI infants have the opportunity to emulate the native-language attunement process and subsequently achieve language development outcomes comparable with their NH peers.

CHAPTER 1

OVERVIEW

1.1 The Research Problem

On almost any given day in Australia a baby is diagnosed with a HL, and hence the research question that motivated this thesis is asked virtually every day in hospital audiology clinics across the country. When amplifying speech for young HI infants, what type of spectral shape is most appropriate for facilitating the acquisition of spoken language? Despite HI infants now being diagnosed as newborns and fitted with hearing aids within the first weeks of life, there has been no systematic research on how different amplification patterns might help or hinder speech perception in the first year. To investigate this issue, it is first necessary to gain an understanding of how NH infants perceive native speech contrasts in which the natural spectral shape has been modified. Speech has a natural negative spectral slope of -3 to -5 dB/octave above 800 Hz (Byrne et al., 1994) which means that the amplitude of successive component frequencies above 800 Hz decreases as the frequency level increases. In this study, the spectral shape of the speech contrasts was modified by the application of a negative spectral tilt, which amplifies low-frequency information and attenuates high-frequency information; a positive spectral tilt, which amplifies high frequencies and attenuates low frequencies; or it remained unmodified.

The specific objective of this thesis was to examine the effect of positive, negative and unmodified spectral tilt on NH infants' ability to discriminate three segmental speech contrasts (high-frequency fricatives, mid-frequency approximants, and low-frequency vowels). As will be shown in the literature reviewed in the introductory chapters, NH infants' speech production and perception develop from an initial language-general mode to one of increasing language specificity by the end of the first year. Thus, this study addresses the issue of whether the perceptual reorganisation that occurs in the latter half of the first year, as infants are acquiring a detailed knowledge of their native language, affects the way they discriminate speech contrasts with modified spectral tilt. This research not only has important theoretical implications for NH infants and how modifying the spectral profile of native speech sounds might affect their perception, it also has important practical implications for specifying the type of amplification most suitable for HI infants.

1.2 Structure of the Thesis

The introductory chapters provide the background literature necessary to establish the research context. The following two chapters provide a review of the development of hearing and language in NH children. Chapter 2 details the development of speech production, and chapter 3, speech perception. In chapter 2 there is an overview of the special speech register produced by mothers talking to their infants – infant-directed speech (IDS), together with the developmental changes in infants' response to IDS. This is followed by a review of how NH infants' speech production becomes more language-specific as it develops from the earliest vocal attempts to the first-word stage. Chapter 3 describes the prenatal auditory environment, and the development of auditory abilities during the infant's first year. This is followed by a description of how infants perceive both the suprasegmental and segmental aspects of language, and how exposure to the native language redefines speech perception.

Chapter 4 outlines hearing impairment, its incidence in Australia, and outcomes for HI children prior to the advent of newborn hearing screening, while chapter 5 discusses the positive impact that early identification of HL has had in terms of improving outcomes for HI children. This brings the reader to the research problem that the current study seeks to address: What is the most appropriate amplification strategy for infants during the earliest stages of language acquisition? Chapter 6 outlines the approach taken in this study, in which NH infants' perception of spectrally modified speech sounds was examined at two developmentally significant ages.

Chapter 7 sets out the design of the three experiments and describes the methods used to address the research question. Chapters 8, 9 and 10 present the results of the three experiments examining infants' discrimination of: fricatives (chapter 8), approximants (chapter 9), and vowels (chapter 10). In conclusion, chapter 11 provides a general discussion of the experimental findings and their implications for both NH and HI infants. Potential future studies are discussed, together with preliminary suggestions for amplification strategies and intervention programs for HI infants.

CHAPTER 2

LANGUAGE DEVELOPMENT: PRODUCTION

One of the most important developmental goals for both NH and HI infants is to learn to speak and use language at an age-appropriate level. This chapter examines speech production, both to the infant (IDS) and by the infant, and how these productions change with increasing language experience. In the first part of the chapter, the linguistic, attentional, and affective characteristics of mothers' production of IDS are described. This is followed by a discussion of how both mothers' production of IDS and infants' response to IDS are modified across the first 12 months. The second part of the chapter outlines the development of infants' production of the suprasegmental and segmental aspects of their native language as they progress from their first coo, through the various babbling stages to uttering their first words.

2.1 Human Speech and Language

The primary form of communication used by humans is speech, a complex acoustic signal produced when air from the lungs passes through the larynx and vocal tract before exiting the mouth or nose. Speakers produce different sounds by changing the position of various articulators, such as the tongue and lips, which alters the flow of air through the vocal tract and creates different speech sounds (Clark & Yallop, 1990). Although speech is heard as a continuous flow of sounds, it contains discrete words, which are formed from combinations of segments. Segments or phones are individual consonant and vowel sounds (e.g., [b] as in *big* and [i] as in *beat*) and each language creates meaning by using only a subset of all possible speech segments. These are known as phonemic segments (or phonemes) and they can be recognised by virtue of their ability to alter meaning. For example, the word *bag* is comprised of three phonemes – /b/, /æ/ and /g/. Each can be replaced with another to change the meaning of the word. For instance, /b/ could be replaced with /n/ to form the word *nag* or /æ/ could be replaced with /ɪ/ forming the word, *big* and so on.

Phonemes in a particular language are idealised categories that may be realised by one or more phones (or allophones). For example, in English the phoneme /p/ has two allophones because it is produced as an aspirated bilabial stop [p^h] as in *pool*, or as an unaspirated bilabial stop [p] as in *spoon*.

Suprasegmental or prosodic aspects of speech are those features of language which occur over and above segments at the sentence, clause, phrase, word, or syllable level. They include features such as rhythm, stress, and intonation and are realised acoustically by variations in fundamental frequency (F0; realised as pitch); intensity (loudness); and the duration of syllables, words, and pauses. Prosodic features convey a wide range of linguistic and social information and are an integral part of speech communication (Clark & Yallop, 1990). Stress is the prominence or emphasis assigned to a syllable or word and it results primarily from increased pitch, and to a lesser extent, increased duration and loudness (Cruttenden, 1986). At the syllabic level, stress can be used to signal whether a word is a noun or a verb (e.g., stress on the second syllable of *present* signals that it is a verb, while stress on the first syllable indicates a noun); and in stress-timed languages such as English, it is used as a rhythmic timing device (see section 3.3.1.1). Alternatively, stress on a particular word can be used by speakers to convey additional information (e.g., *Jane was leaving* vs. *Jane was leaving*). Intonation refers to the pattern of rising and falling pitch levels over a word, phrase, or sentence. It can be used to indicate whether a string of words is a question or statement (e.g., rising intonation at the end of a phrase signals a question) and also to convey a speaker's attitude or intent (e.g., a falling contour is associated with certainty; Halliday, 1970).

2.2 Infant-directed Speech

Infants acquire language seemingly without effort. One of the factors which might expedite infants' efficient acquisition of their native language is the special speech style used when talking to infants known as IDS. IDS has been described in a variety of languages including English (Fernald et al., 1989); German (Fernald & Simon, 1984); Japanese (Fernald & Morikawa, 1993); and Thai (Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin, 2002). Typically, IDS has a higher mean F0 and larger pitch range than adult-directed speech (ADS); shorter, slower, simpler utterances; hyperarticulated vowels; and elevated levels of positive affect (Fernald &

Simon, 1984; Kitamura & Burnham, 2003; Kuhl et al., 1997; Snow & Ferguson, 1977; Stern, Spieker, Barnett, & MacKain, 1983). Researchers have proposed that mothers[2] use IDS mainly as a means of engaging their infant's attention (e.g., Fernald & Simon, 1984; Werker & McLeod, 1989) and communicating affect (e.g., Fernald, 1989, 1992; Kitamura & Burnham, 2003). It has also been suggested that the features of IDS play a role in facilitating the acquisition of language (Liu, Kuhl, & Tsao, 2003).

2.2.1 Linguistic Benefits of IDS

The idea that IDS might play a role in infants' acquisition of language is not new. Ferguson (1964) first proposed that the simplified vocabulary, short utterances, repetition, and exaggerated prosody in IDS might be didactic devices used by mothers to 'teach' their infants to speak (see also Lacerda & Sundberg, 2006). Experimental evidence shows that the exaggerated prosody in IDS, but not ADS, facilitates infants' segmentation of words (Thiessen, Hill, & Saffran, 2005); clauses (Hirsh-Pasek et al., 1987); and segments (Karzon, 1985; Trainor & Desjardins, 2002). Karzon (1985) found that 1- to 4-month-olds can only discriminate the polysyllabic sequences /malana/ versus /marana/ when stress falls on the middle syllable as is typical of IDS, but not when monotonic intonation is used. Similarly, 6- to 7-month-old infants discriminate the vowels /i/ and /ɪ/ better when the F0 contour is shaped than when it is monotonic (Trainor & Desjardins, 2002). Furthermore, hyperarticulation of vowels and consonants has been proposed to facilitate infants' acquisition of native sound categories. Bernstein Ratner (1984) was the first to suggest that, when talking to infants, adults adjust the clarity of their speech. Instead of producing the typically indistinct and highly variable phonetic units found in ADS, mothers produce acoustically well-specified speech sounds that provide infants with discriminable exemplars that are necessary for language learning.

2.2.1.1 Vowels in IDS

There is considerable evidence showing that IDS vowels not only have longer duration and higher F0 than those of ADS (Bernstein Ratner & Luberoff, 1984), but they are also hyperarticulated (Burnham, Kitamura, & Vollmer-Conna, 2002; Kuhl et al., 1997). That is, vowels are realised with less overlap and greater separation

[2] Although fathers and other carers also use IDS (Fernald et al., 1989), mothers tend to be infants' primary caregivers and are therefore the most studied users of IDS.

between categories, making them more distinct and thus more intelligible to the listener. In the case of the three ‘corner’ vowels, /i/, /u/, and /a/, F1 and F2 are modified in order to acoustically ‘stretch’ the vowel triangle that is formed by the three vowel points in F1-F2 space (Burnham et al., 2002; Kuhl et al., 1997). An early longitudinal study of infants suggested that hyperarticulation of vowels increased as infants progressed from the preverbal to one-word stage and beyond (Bernstein Ratner, 1984). More recent studies suggest that vowel hyperarticulation is present in speech to infants aged around 4 months (Kuhl et al., 1997) and in languages such as English, Russian, Swedish, and Mandarin (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003).

The issue of whether or not vowel hyperarticulation assists infants to acquire language has been investigated in a number of ways. Burnham et al. (2002) compared vowel production in IDS and a similarly intonated speech style, pet-directed speech (PDS). Vowel hyperarticulation was evident in IDS but not PDS, suggesting that mothers are sensitive to the language-learning potential of the listener, and that they may be using vowel hyperarticulation as a didactic device to assist their infants to learn native-language vowel structure. Liu et al. (2003) approached this issue in a different way. They showed that there is a link between the degree of hyperarticulation in a Mandarin-speaking mother’s IDS vowels and her infant’s ability to discriminate a native-language consonant contrast. That is, the size of the mothers’ vowel triangles was significantly correlated with infants’ consonant discrimination scores suggesting that vowel hyperarticulation assists infants’ acquisition of native-language speech sounds generally, not just vowels.

More recent evidence suggests that vowel hyperarticulation provides distributional cues to native vowel categories. Werker and colleagues (2007) asked Japanese- and English-speaking mothers to ‘teach’ their 12-month-old infants a set of non-words. The Japanese non-words contained a pair of vowels that differed primarily in duration, whereas the English non-words contained vowel pairs that differed spectrally (i.e., the vowels had different F1 and F2 values). The results showed that mothers’ speech provided exaggerated language-specific cues – Japanese mothers’ vowels differed significantly in duration, but not in terms of F1 and F2; whereas English mothers’ vowels were well-differentiated in terms of F1 and F2 values, but not duration. Regression analyses confirmed that the distribution of the duration cue resulted in two clearly delineated vowel categories in Japanese, while in English, the two vowel categories were formed on the basis of their formant differences. These findings suggest that the specific acoustic features that mothers hyperarticulate in IDS are closely aligned to the acoustic features that differentiate vowel categories in different languages.

2.2.1.2 Consonants in IDS

Less work has been conducted on consonants in IDS, likely because consonants tend to be discrete sounds incapable of being exaggerated in the same way as vowels. Nevertheless, voice onset time (VOT) or the time between the onset of vocal cord vibration and the release of a stop (Lisker & Abramson, 1964) has been identified as a way of assessing consonant hyperarticulation in IDS. Not only is VOT a continuous dimension that talkers adjust to distinguish between different stop-consonant categories, but lengthening or shortening it tends to make stops more or less distinct from one another. Some, but not all, studies show that mothers exaggerate VOT in IDS compared to ADS. In Norwegian, mothers of infants aged 1 to 6 months lengthen their VOTs for alveolar and velar, but not bilabial, stops (Englund, 2005). In Swedish, mothers underspecified the VOTs of stops for infants at 3 months (Sundberg & Lacerda, 1999), but increased them at 12 months (Sundberg, 2001). Studies of IDS in English found larger VOTs and less overlap between voiced and voiceless stops in IDS to 15- to 16-month-olds, but not to preverbal infants or those aged over 2 years (Malsheen, 1980). Thus, there is evidence that mothers not only exaggerate their vowels, but also the VOTs of stop consonants in IDS.

2.2.1.3 Tones in IDS

Recently, evidence of hyperarticulation of lexical tones has been reported in IDS in two tonal Chinese languages, Mandarin and Cantonese. Liu, Kuhl and Tsao (2007) reported that in Mandarin IDS to infants aged between 10 and 12 months, mothers increase the F0 and durational differences amongst lexical tones, thus exaggerating their distinctiveness. Similarly, a longitudinal study of Cantonese IDS found that tone hyperarticulation is present in the speech of mothers talking to infants aged between 3 and 12 months (Xu, Burnham, & Kitamura, 2007). The authors plotted the F0 onset and offset values of the three most disparate 'corner' tones of Cantonese to create 'tone triangles' analogous to the vowel triangles used in studies of vowel hyperarticulation (e.g., Burnham et al., 2002; Kuhl et al., 1997). The IDS tone triangles were enlarged compared to those of ADS, with the most exaggerated tone production occurring between 6 and 9 months. This peak at 6 to 9 months is of particular relevance because it occurs at the same age that infants are narrowing their perceptual focus to native-language lexical tones (Mattock & Burnham, 2006).

2.2.2 Affective Intent in IDS

Mothers from different language groups convey approval, attract attention, prohibit an action, or comfort their infant using specific contour shapes (Fernald, 1992). For example, in French, German, Italian, and English IDS, approving utterances typically have high mean F0, wide F0 range, and a rise-fall contour; while comforting utterances tend to have lower mean F0, a narrower F0 range, and a long, falling F0 contour (Fernald, 1992). The effectiveness of IDS pitch contours in conveying parental messages has been demonstrated by Fernald (1989). On the basis of intonational information only, adults more reliably and easily categorised the affective intent in IDS than ADS utterances in five interactional contexts: attention-bid; approval; prohibition; comfort; and a game (Fernald, 1989). Even adults from a non-industrialised, indigenous Ecuadorian population are able to accurately identify the affective intent in American English IDS (Bryant & Barrett, 2007). Importantly, infants are also responsive to IDS contours. Fernald (1993) reported that 5-month-old English-learning infants show appropriate affective responses to approving (rising) and disapproving (falling) IDS contours whether they are presented in native English, or non-native German or Italian.

Developmental evidence shows that the affective and intonational characteristics of IDS are modified as the infant gets older (Kitamura & Burnham, 2003; Stern et al., 1983). A longitudinal study by Kitamura and Burnham (2003) measured F0 characteristics and affective intent in mothers' speech at birth, 3, 6, 9, and 12 months. For affective intent, adults listened to low-pass filtered samples recorded at each age and were asked to judge the mother's level of affect, and her intention to convey affection; comfort or soothe; and direct behaviour. For newborn IDS, in which mean F0 and F0 range were at their lowest, the most highly rated maternal intention was to 'comfort or soothe'. At 6 months, when pitch measures were at their highest, the most highly rated intention was to 'express affection', while at 9 months when the pitch measures declined substantially, mothers' speech was rated as expressing much lower levels of positive affect and most highly for the intention to 'direct behaviour'.

Interestingly, it appears that infants' responses to IDS correspond with changes in mothers' production of IDS. An infant preference study, in which all three affective intent types were played to groups of infants, revealed that 3-month-olds prefer comforting, 6-month-olds prefer approving (and comforting), and 9-month-olds prefer directive (and approving) affective intent over the other types (Kitamura & Lam, 2009). Moreover, there is evidence that mothers adjust the prosodic and linguistic characteristics of IDS in response to their infants' experience with speech, rather than simply their age. A recent study by Bergeson, Miller, and McCune (2006) found that the IDS of mothers of children with cochlear implants was more similar (in terms of pitch, timing and utterance complexity) to the IDS of mothers of NH children who matched the implant recipients for hearing experience rather than age. In other words, irrespective of the hearing status of their children, mothers produce prosodically similar IDS for children who have been exposed to speech for the same period of time.

2.2.3 Infant Attention to IDS

Even at birth, infants show a preference for IDS, with studies showing that 2-day-olds and 1-month-olds prefer to listen to IDS rather than ADS (Panneton Cooper, Abraham, Berman, & Staska, 1997; Panneton Cooper & Aslin, 1990) when the female talker is not their own mother. When listening to their mother's voice, young infants show no preference for IDS over ADS, which suggests that they like listening to their mother's voice regardless of the speech style she is using (Panneton Cooper et al., 1997). Between 3 and 5 months of age, infants' preference for IDS is consolidated such that they prefer to listen to IDS over ADS, whether the speaker is their mother or an unknown female (Fernald, 1985; Panneton Cooper et al., 1997);

male or female (Werker & McLeod, 1989); or using a native or non-native language (Werker, Pegg, & McLeod, 1994).

It has been proposed that the basis of infants' preference for IDS is either its exaggerated intonation (Fernald & Kuhl, 1987) or its highly affective style (Kitamura & Burnham, 1998; Singh, Morgan, & Best, 2002). Fernald and Kuhl (1987) used sine-wave analogues of IDS to show that the exaggerated F0 accounted for IDS preferences, rather than its amplitude or duration patterns. However, it has also been shown that when the mean F0 is matched in two samples of IDS, 6-month-old infants listen longer to IDS with high, rather than low, levels of positive emotion, but show no preference when emotion is matched and F0 varied (Kitamura & Burnham, 1998). Similarly, 6-month-olds listen longer to happy than neutral speech, whether it is presented in the IDS or ADS register (Singh et al., 2002).

Evidence is accumulating to show that around 8 months of age, infants' preference for IDS diminishes. Hayashi et al. (2001) found that infants aged 4 to 6 months and 10 to 14 months paid more attention to IDS than ADS, whereas a group aged 7 to 9 months did not respond differentially to the two speech types. Panneton, Kitamura, Mattock, & Burnham (2006) have also shown that at 4 months of age, infants pay more attention to speech with slowed tempo whereas at 8 months, they prefer speech with a normal tempo. They also found that 4-month-olds' preference for IDS with high positive affect dissipates by 8 months of age (Panneton et al., 2006). Similarly, when infants aged between 6 and 10 months listen to vowels with bell and monotonic contours that are of normal or slowed duration, 6-month-olds listen longer to vowels with bell contours and slow duration, but 10-month-olds listen longer to vowels with monotonic contours and normal duration (Kitamura & Notley, in press).

2.2.4 Conclusion

IDS throughout infancy is often characterised in a relatively generic way, but there is a substantial body of evidence to suggest that IDS might be better described as a heterogenous phenomenon that changes significantly depending on the age of the infant listener. For instance, mothers' speech to 9-month-olds has reduced levels of F0 and less positive affect compared to their speech to 6-month-olds (Kitamura & Burnham, 2003). It is notable that these changes in mothers' speech take place at the same time that infants show a diminished preference for IDS. Certainly, the research presented in this chapter suggests that mothers tune into their infants' phase of development (Bergeson et al., 2006) and that infants are also sensitive to their mothers' speech during each developmental phase (Kitamura & Lam, 2009). These findings remind us that IDS is not a one-sided affair. Rather, it is a reciprocal exchange between mother and infant, during which the infant makes his or her first communicative attempts.

2.3 Development of Infants' Speech Production

Throughout the first year of life, infant vocalisations become more adult-like and exhibit increasing linguistic sophistication, and it is to this topic that we now turn. This section examines the developmental stages of infants' speech production, examining, in particular, how infants' vocalisations are gradually refined from an initial language-general repertoire of underspecified speech-like sounds to the increasingly language-specific phonetic units of their mother tongue.

2.3.1 Infants' Prelexical Vocalisations

During the first 12 months infants progress through a universal series of prelexical or babbling stages (Oller, 2000; Vihman, 1996). There is considerable overlap in the type of vocalisations produced in each stage as many of the sounds typical of one stage continue to occur in the next stage (Oller, 1980; Stark, 1980). Nevertheless it is possible to divide infants' early vocalisations into consecutive stages which are differentiated by the predominance of the sound types produced in each one. In the first 1 to 2 months infants produce very few speech-like sounds. Most commonly they produce reflexive or vegetative sounds – involuntary noises related to discomfort (e.g., crying) or bodily functions (e.g., grunts, sneezes and coughs; Oller, 1980; Stark, 1980). From 2 to 4 months of age, infants start to produce coos (Stark, 1980) or 'primitive articulations' combining mostly velar consonant-like sounds with a range of vowel-like sounds (Oller, 1980, 2000). Around 4 to 6 months of age, infants enter the expansion stage (Oller, 1980) or the vocal play period (Stark, 1980), in which there is greater variability in infants' vocalisations. The infant produces isolated vowel-like sounds; and raspberries, squeals, growls and yells are also common. In addition, marginal or precanonical babbling emerges, that is, immature syllables comprising a vocal tract closure followed by a slow transition to a vowel-like nucleus (Oller, 1980, 2000).

Following the first prelexical babbling stages, an important milestone in the development of speech production occurs quite abruptly at around 7 to 8 months of age – infants begin to produce canonical babbling (Roug, Landberg, & Lundberg, 1989; van der Stelt & Koopmans-van Beinum, 1986). Canonical syllables have the form and timing characteristics of syllables found in adult speech and comprise a complete well-formed vowel or vowel-like sound, with at least one ‘articulated margin’ or consonant-like sound involving complete or near-complete closure of the vocal tract (Oller, 1980). To qualify as a ‘canonical’ syllable, the transition between consonant and vowel components must be less than 120 msec (Oller, 2000). Canonical syllables are often repeated or ‘reduplicated’, (e.g., *bababa*, *dadada*) but not always (Oller, 1980). Most infants are producing canonical syllables frequently and reliably by 10 months (Oller, 2006), and around 11 to 12 months of age, infants start to diversify their babbling even more by varying the consonants and vowels produced in a string (e.g., *badabepita*). Oller (1980) refers to this period as the ‘variegated babbling stage’. Canonical babbling is regarded as a key milestone because in the majority of cases, infants’ first words appear within a few months of its onset (Oller, Levine, Cobo-Lewis, Eilers, & Pearson, 1998).

One of the most striking features of infant babbling is the similarities observed in the characteristics of infant babble from different language environments (Locke, 1983; Nakazima, 1962; Oller, Eilers, Urbano, & Cobo-Lewis, 1997). Locke’s (1983) study of the babbling of infants from 15 language backgrounds revealed that independently of language, the CV syllable is more commonly produced than other syllable forms, and there is a remarkable commonality among the sound inventories. Stops and nasals are the most prevalent sounds, followed by approximants, whereas sounds that are rare in the world’s languages, such as aspirated fricatives and retroflex consonants, are also rare in infant babbling (Locke, 1983; Oller et al., 1998). Researchers such as Locke (1990) and MacNeilage (2000) contend that the reason the same sounds commonly occur in babbling across languages is that these sounds are the easiest to produce for both infants and adults.

2.3.2 Development of the Vocal Tract and Speech Motor Control

Throughout the infant's first 18 months, but particularly during the early babbling stages, vocalisations are constrained by the size and shape of the vocal cavity, which differs substantially from the adult's in several ways: the larynx is higher; the vocal tract is shorter; the pharyngeal cavity (between the back of the nose and the upper end of the airway) is shorter; the tongue is large relative to the oral cavity; and the angle of the back portion of the vocal tract is less sharp (Stark, 1980; Vihman, 1996; Vorperian et al., 2005). Because the larynx is high in the throat, breathing occurs predominantly through the nasal cavity (Kent, 1981), and consequently, the vocalisations of the young infant are highly nasalised. At around 4 months of age, the infant's vocal tract undergoes rapid and significant growth; the larynx drops, which increases the length of the pharyngeal cavity; and the angle between the oral and pharyngeal cavities becomes sharper (Kent, 1981). These changes allow the tongue to move more freely which, together with development of the respiratory system (Langlois, Baken, & Wilder, 1980), means that the infant can start to produce a greater range of vocalic and consonantal sounds (Sussman, Duder, Dalston, & Cacciatore, 1999).

Infants' early vocalisations are also limited by immature neuromuscular control of the vocal tract (e.g., Netsell, 1981; Vihman, 1996). As the infant matures, its motor control of the lips, tongue and jaw (as well as other parts of the body) increases (Kent & Murray, 1982; Sussman et al., 1999; Thelen, 1981). In particular, it has been noted that the onset of canonical babbling co-occurs with the onset of other motor skills such as right-handed reaching and rhythmic hand actions (Ramsay, 1984; Thelen, 1981). The parallel development of right-handed movements and the onset of canonical babbling suggests that this advanced stage of babbling might arise as a result of left-hemispheric maturation, which provides the motor control necessary for infants to start producing well-formed syllables. As yet, there is no direct evidence of the physical source of neurological speech motor control (Polka, Rvachew, & Mattock, 2007), although various theoretical models have attempted to explain the link between brain maturation and the development of babbling (e.g., MacNeilage, 1998; Sussman, 1984).

2.3.3 Experiential Influences on Infants' Prelexical Vocalisations

The staged emergence of infant babbling, together with the commonalities in infant babble from different language communities, suggest that infants' prelexical vocalisations unfold along a universal course that is largely determined by vocal tract anatomy and neural maturation (Locke, 1993; Oller, 2000). Although few would deny the obvious universal and maturational aspects of infant babbling, it is also true that auditory experience plays a role in the development of babbling because infants with profound HL start producing canonical babble later than NH infants (Eilers & Oller, 1994; Oller & Eilers, 1988), and the age at which infants receive amplification or cochlear implantation is also correlated with the onset of babbling (Eilers & Oller, 1994; Schauwers, Gillis, Daemers, De Beukelaer, & Govaerts, 2004). See section 5.1 for more detail. Even NH infants who experience otitis media (and resultant temporary conductive HL) during their first 6 months produce less canonical babbling than those with no history of otitis media (Rvachew, Slawinski, Williams, & Green, 1999).

Clearly, general auditory experience affects both the onset and quality of infants' early vocalisations, but does *specific* auditory experience also influence early vocalisations? A striking demonstration of the influence of language exposure on infants' vocalisations was reported by Kuhl and Meltzoff (1996). They found that exposure to a particular vowel type (during three 5-minute recording periods) led to an increase in 3- to 5-month-olds' productions of that particular vowel. This result suggests that accumulated exposure to native speech sounds will influence infants' vocalisations such that they will increasingly resemble the sounds of the native language. Although a small number of studies have suggested that infants' prelexical babbling does not gravitate towards the native language (Oller & Eilers, 1982; Olney & Scholnick, 1976), the majority of studies indicate that attunement to the ambient language does occur in babbling, and furthermore, it occurs during the first 12 months (e.g., De Boysson-Bardies, Halle, Sagart, & Durand, 1989; De Boysson-Bardies & Vihman, 1991). These studies are reviewed below.

One way of investigating whether infants modify their babbling to reflect the characteristics of the ambient language is to ask adults to identify the language background of the infant who produced the babbling sounds. An early study by Olney and Scholnick (1976) found that phonetically untrained English-speaking adults could not identify the language background of a Cantonese- versus English-learning infant recorded at 6, 12 or 18 months. In a larger study, Thevenin, Eilers, Oller, and Lavoie (1985) asked untrained English-speaking and bilingual Spanish-English adults to listen to babbling from seven English- and seven Spanish-learning infants aged 7 to 10 months and 11 to 14 months. Both groups of adults failed to identify the language background of the utterances above chance level, although some judges were more successful than others.

Other research has been more successful in this endeavour. A study by De Boysson-Bardies, Sagart, and Durand (1984) found that untrained French speakers could distinguish babble produced by (i) French- versus Arabic-learning infants at 8 and 10 months of age, and (ii) French- versus Cantonese-learning infants at 8, but not 10, months of age. This study also found that expert phoneticians are better than untrained listeners at distinguishing the babble of French- versus Arabic-learning infants, even when produced by infants as young as 6 months. Similarly, a panel of five expert phoneticians was able to identify the language environment of 12- and 18-month-old Swedish and American infants' babbling samples (Engstrand, Williams, & Lacerda, 2003). When the experts were asked whether their decisions were based on the quality of the consonants and vowels, or suprasegmental cues, such as accent or stress, they found that the most reliable cue used by the judges was pitch accent – a key suprasegmental feature of Swedish that is not used in English. Hence, the authors suggest that the suprasegmental aspects of speech may provide primary cues to language specificity in babbling (Engstrand et al., 2003).

De Boysson-Bardies and colleagues (1984) have also suggested that infants' babble can be differentiated more successfully based on suprasegmental than segmental cues. They showed that when the babble of French- and Arabic-learning infants was 'highly articulated' and 'poor in intonation patterns' neither phonetically trained nor untrained listeners could identify the language background of the infant babble above chance. However, when the babble comprised long utterances with 'pitch patterns spreading over the whole breath-group', both expert and non-expert listeners were successful. Thus, it is seems that the prosodic characteristics of babbling are its most salient feature, and as we will see, these become language-specific quite early in the first year.

2.3.3.1 Language-specific Prosody in Babbling

So far, all the studies discussed have used adult judgements to assess whether infant babbling approximates the characteristics of the native language. However, more recent studies have conducted acoustic and phonetic analyses to address this issue. In a comparison of babbling by French- and English-learning infants aged between 5 and 13 months, Levitt and Wang (1991) reported cross-language differences that reflected the different suprasegmental characteristics of French and English. In French, syllable lengthening tends to occur at the end of utterances whereas English tends to exhibit lengthening on all stressed syllables regardless of whether or not they occur in final position (Fletcher, 1991). As expected, twice as many of the French-learning infants' final syllables were lengthened compared to their English-learning peers. Furthermore the magnitude of the final-syllable lengthening produced by French-learning infants was much greater than that of English-learning infants. Similarly, Halle, De Boysson-Bardies, and Vihman (1991) reported French-learning 18-month-olds produce significantly longer final syllables than do Japanese-learning children; and Levitt and Aydelott Utman (1992) reported more final-syllable lengthening in a French infant's babble compared to that of an English-learning infant, with the difference being more pronounced at 14 months than at earlier ages.

Further evidence that infants' prelexical productions tend to reflect the suprasegmental details of the native language was reported by Whalen, Levitt, and Wang (1991). They found significant differences in the intonation contours of French- versus English-learning infants' babbling at 5 to 13 months – the French-learning infants produced more rising contours, and the English-learning infants produced mostly falling contours. These patterns reflect the relative occurrence of rising and falling intonation contours in adult productions of French and English (Delattre, 1961). Similarly, Halle et al. (1991) found significant differences in the intonation contours of disyllabic utterances produced by Japanese- and French-learning 18-month-olds. Again, in line with the adult language characteristics, French-learning infants produced significantly more rising contours, while the Japanese-learning infants produced more falling contours. The findings detailed above show that native-language suprasegmental patterns have systematic effects on the infant's early vocalisations. The next section details how the quality of babbled vowels also seems to reflect the infant's ambient language.

2.3.3.2 Language-specific Vowels in Babbling

In general, the vowels produced by babbling infants become more adult-like over time (Bond, Petrosino, & Dean, 1982; Buhr, 1980; Lieberman, 1980). The infant's vowel space expands in parallel with their expanding vocal tract (Kent & Murray, 1982; Rvachew, Mattock, Polka, & Ménard, 2006) and increased neuromuscular control of the lips, jaw and tongue (Buhr, 1980). Maturational effects on early vowel production can be seen in results which show that F1 and F2 of infants' vowel-like productions become increasingly more differentiated between 3 and 5 months (Kuhl & Meltzoff, 1996) and between 10 and 18 months of age (Rvachew, Alhaidarya, Mattock, & Polka, 2008).

In addition to these maturational effects, there is evidence that the ambient language influences infants' production of vowels. For instance, systematic inter-language differences emerged when De Boysson-Bardies et al. (1989) examined the vocalic utterances of 10-month-olds from French, English, Arabic, and Cantonese language environments. F1 and F2 values were plotted in vowel space and the results showed that the vowels of infants from different language groups were more distant from each other than those from within any one language group. Additionally, when the mean F2/F1 ratio for each language was calculated, English had the highest ratio indicating that the vowels of English-learning infants were the most diffuse or separated, followed by French, Arabic, and Cantonese, in which the vowels were more compact. This trend from diffuse-to-compact follows the same sequence found in the adult vowel systems of these languages. Similarly, analyses of vowels produced by French- and English-learning infants show that their respective vowel spaces diverge between 12 and 18 months of age (Levitt & Aydelott Utman, 1992; Rvachew et al., 2006).

Analysing infants' vowel repertoires is also indicative of whether infants' vocalisations are gravitating to their native language. The English- and French-learning infants in Levitt and Aydelott Utman's (1992) study produced essentially the same set of vowels, but there was some evidence of language-specific distribution. For example, from as early as 5 months of age, the English-learning infant favoured production of the frequently occurring English vowels /ə/, /æ/, and /a/, while he rarely produced /e/, which is relatively infrequent in adult English. Less clear distribution patterns were reported for the French-learning infant. Oller and

Eilers (1982) analysed the vowel repertoires of Spanish- and English-learning 12-month-olds, and although they contained similar vowels, there were also language-based differences. For example, Spanish uses /a/, /e/, /i/, /o/, and /u/ more frequently than English, and the Spanish-learning infants produced higher proportions of these vowels than their English-learning counterparts. Similarly, 7 of the 10 vowels that are more common in English than in Spanish were produced in greater numbers by English- than Spanish-learning infants. Taken together, these studies reveal that the ambient language exerts considerable influence over infants' vocalic productions as early as 5 months of age.

2.3.3.3 Language-specific Consonants in Babbling

Not surprisingly, infants' early consonantal productions also start to resemble those of the native language as infants' experience with the native language increases. In a cross-language longitudinal study of infants' consonantal repertoires, De Boysson and Vihman (1991) found that between 9 and 19 months of age, French-learning infants produced significantly fewer stops than infants from an English, Japanese, or Swedish background; and more labials than Japanese- and Swedish-learning infants, a pattern that is consistent with the relative distribution of consonants in these four languages. Levitt and Aydelott Utman (1992) also found that between 5 and 14 months of age, infants increased their production of native-language consonants, while decreasing production of non-native consonants. Thus, by 14 months, infants' emergent consonant inventories had started to resemble those found in the ambient language environment.

Another way of investigating whether infants modify their babbling to reflect the characteristics of the ambient language is to measure whether the VOTs of stop consonants differ in accord with native language productions. For instance, French stop consonants either have negative (prevoiced) or positive (short lag) VOT (Caramazza & Yeni-Komshian, 1974), whereas English only has positive VOT: either short-lag or long-lag with aspiration (Lisker & Abramson, 1964). Whalen, Levitt, and Goldstein (2007) found little or no difference in the VOT durations produced by French- and English-learning 9- to 12-month-olds. However, a significant language difference was found in terms of the *proportion* of prevoiced VOTs produced: French-learning infants produced approximately three times as many as English-learning infants, which reflects the incidence of prevoiced VOTs in adult spoken French (Delattre, 1965). These results echo those of Eilers, Oller, and Benito-Garcia (1984), who found that the VOTs of Spanish-learning infants did not differ from those of English-learning infants at 12 months of age. However, by the time the infants had reached 24 months of age, around half of them were producing their respective native voicing categories contrastively.

2.3.4 Conclusion

During the first six months of life, infants' prelexical vocalisations unfold in a universal fashion, albeit constrained by anatomical and neuromuscular factors (Locke, 1993). Just prior to the onset of canonical babbling at 7 to 8 months of age, the influence of the ambient language becomes evident and infants' vocalisations start to exhibit signs of language specificity. The evidence available to date suggests that infants first gravitate to the suprasegmental characteristics of their native language and produce syllables based on native-language durational and intonational patterns as early as 5 to 6 months of age (Levitt & Wang, 1991; Whalen et al., 1991). There is also evidence that the segmental characteristics of infant babbling become more like those in the native language environment. Vowel repertoires reflect native-language vowel distributions from around 5 months of age (Levitt & Aydelott Utman, 1992), while consonant repertoires begin to emulate the proportions found in the adult language from around 9 months of age (De Boysson-Bardies & Vihman, 1991). As will be seen in the next chapter, the development of infant speech production tends to mirror the development of infant speech perception. That is, infants attend to the suprasegmental aspects of speech from birth; are acquiring native language vowel inventories at around 6 months of age; and consonant inventories at around 9 months of age.

CHAPTER 3

HEARING AND LANGUAGE DEVELOPMENT: PERCEPTION

The purpose of this chapter is to describe the developmental progress of infants' auditory and speech perception abilities. The chapter begins with a description of infants' prenatal auditory experiences, which is followed by an examination of how infants' auditory abilities develop during the first year of life. Section 3 of the chapter discusses infants' perception of speech and details how infants' initial acoustic mode of speech perception is transformed as they begin to attune to the details of native-language vowels and consonants.

3.1 Prenatal Auditory Experience

Anatomical studies reveal that the cochlea (see Figure 1) is functioning by about the fifth or sixth month of gestation and is fully matured at birth (Pujol, Lavigne-Rebillard, & Uziel, 1991). In contrast, the external and middle ear structures (see Figure 1) continue to mature after birth, increasing in size and shape into early childhood (Bredberg, 1985). Although the transmission of sound to the fetal ear is compromised by the fluid-filled external and middle ear spaces (Rubel, 1984) and the immaturity of the neural auditory pathway, there is evidence that as early as 24 to 25 weeks, the fetus responds to auditory stimulation (Birnholz & Benacerraf, 1983; Crade & Lovett, 1988; Lecanuet, 1998). At 27 weeks, fetuses respond to low-frequency tones of 250 and 500 Hz, and by 33 to 35 weeks, they respond reliably to tones of 1000 and 3000 Hz (Hepper & Shahidullah, 1994). Thus, fetal hearing improves during gestation, progressively covering a broader range of frequencies and requiring lower levels of intensity to elicit a response.

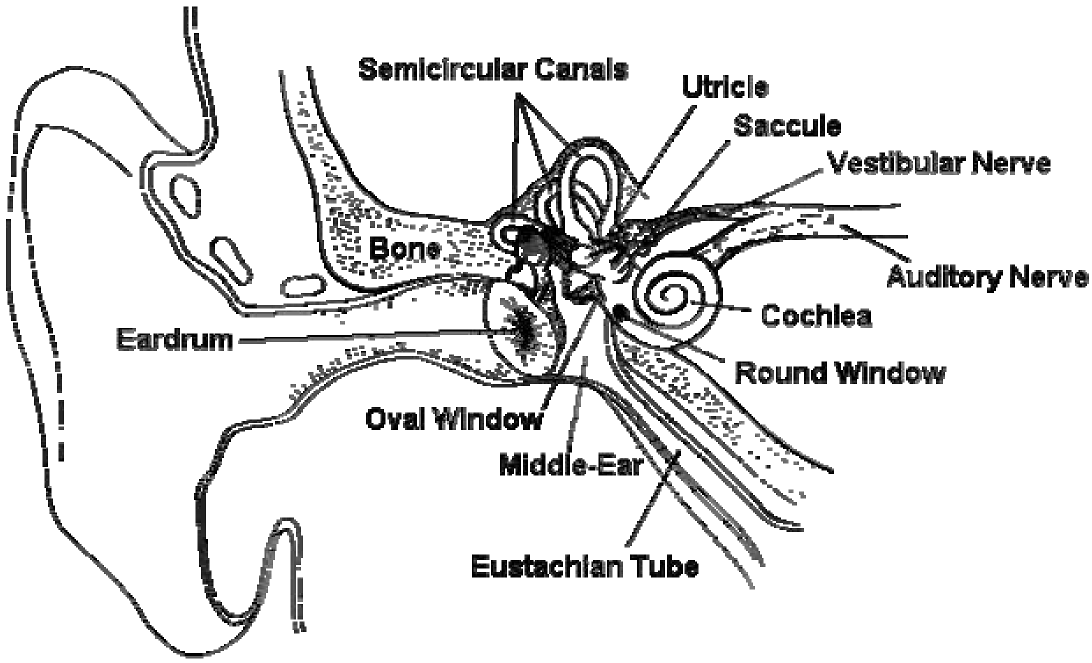

Figure 1. The human ear.
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Prenatally, the fetus is exposed to both extra- and intrauterine auditory events. Studies of pregnant humans and sheep[3] reveal that the uterine acoustic environment is comprised of various cardiovascular, respiratory, and intestinal sounds produced by the mother (Armitage, Baldwin, & Vince, 1980; Querleu, Renard, Versyp, Paris-Delrue, & Crepin, 1988). The sounds are primarily of low frequency and they generate a background noise level between 40 and 60 dB SPL, with higher noise levels recorded for frequencies under 100 Hz (Gagnon, Benzaquen, & Hunse, 1992). Above this background noise, the mother's voice and other extrauterine sounds louder than about 65 dB can be heard (Querleu et al., 1988). Human in-utero recordings reveal that external noises reach the uterine environment in an attenuated form, such that frequencies below 250 Hz are diminished by only 2 dB, while frequencies over 500 Hz are reduced by 14 to 26 dB (Querleu et al., 1988). A study of fetal lambs' cochlear responses to external noise suggests that when frequencies below 500 Hz reach the inner ear they are attenuated by 10 to 15 dB, but frequencies over 500 Hz are attenuated by 40 to 50 dB (Gerhardt et al., 1992). The substantial attenuation of high frequencies in the uterine

[3] Studies of the fetal acoustic environment have been conducted in both humans and sheep because the uterus of a pregnant ewe is acoustically similar to that of humans, and the rate at which hearing develops in humans and sheep is roughly equivalent (Gerhardt & Abrams, 2000).

environment occurs because the mother's abdominal and uterine walls act as a low-pass filter, allowing sounds less than 250 Hz to penetrate the uterus, while sounds above 250 Hz are attenuated at a rate of approximately 6 dB/octave (Gerhardt, Abrams, & Oliver, 1990).

Studies investigating the transmission of voices to the fetal environment reveal that external voices are attenuated by 20 to 24 dB while the maternal voice is reduced by just 8 dB (Querleu et al., 1988). Maternal speech suffers less attenuation than speech from other talkers because it reaches the uterus externally via the air and is also transmitted internally via body tissue and bone (Pujol et al., 1991; Richards, Frentzen, Gerhardt, McMann, & Abrams, 1992). Although uterine recordings occasionally contain audible words, the low-pass filter effect of the mother's abdominal and uterine walls means that speech available to the infant is degraded such that only about 30% of phonemes recorded in utero are intelligible to adult listeners (Querleu et al., 1988). Recordings of a female voice using a microphone placed in the uterus of a pregnant ewe show a similar rate of phonetic transmission, with low-frequency voicing information more intelligible than high-frequency information relating to place or manner of articulation (Griffiths, Brown, Gerhardt, Abrams, & Morris, 1994). In contrast to the poor transmission of high-frequency segmental information to the fetus, the low-frequency prosodic qualities of speech, most of which occur in the frequency range from 100 to 1000 Hz, are well preserved. Human in-utero recordings of a simple lullaby spoken by a mother and other adults show that the intonation contours of the mother and the other speakers reach the fetus virtually intact (Querleu et al., 1988).

The low-frequency aspects of the mother's speech are clearly an important part of the fetal auditory experience because their influence is shown in the infant's preferences at birth. Studies show that newborns prefer their mother's voice over that of an unknown female (DeCasper & Fifer, 1980), but not their father's voice over an unknown male (DeCasper & Prescott, 1984). Newborns also prefer a passage their mother read while pregnant over an unfamiliar passage (DeCasper & Spence, 1986); music heard prenatally over unfamiliar music (Hepper, 1991); and can discriminate between their native language and a non-native one, even when they are low-pass filtered at 400 Hz to leave only prosodic cues intact (Mehler et al., 1988; Moon, Panneton Cooper, & Fifer, 1993). These findings confirm that it is the mother's voice that is heard most clearly and most regularly in utero, and that low-frequency prosodic and rhythmic speech information is particularly salient in this environment.

3.2 Infants' Auditory Abilities

Once infants leave the womb, they experience speech in all its spectral complexity and face the challenge of deciphering the richly varied speech stream in order to acquire their first language and eventually communicate with others. Although infants' prenatal linguistic exposure may predispose them to language, there is evidence that infants begin life equipped with an innate bias to listen to speech. Vouloumanous and Werker (2007) showed that 1- to 4-day-old infants prefer speech rather than complex non-speech analogues matched for duration, pitch, formant structure and amplitude. There is also evidence that humans' brains are specialised to perceive speech because the brains of infants aged between 0 and 10 months respond differentially to speech versus non-speech stimuli (Molfese, Freeman, & Palermo, 1975) and different patterns of brain activity are observed when 3-month-olds listen to forward versus reversed speech (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002).

Whether or not the infant's proclivity for speech is truly innate or the result of prenatal experience, it is nevertheless a valuable tool for the infant about to embark on the journey of language acquisition. But there are other abilities which infants need in order to acquire language. Basic auditory (or non-linguistic) abilities such as the capacity to discriminate changes in frequency and intensity are considered "fundamental to the development of human speech perception and production" (Sinnott & Aslin, 1985, p. 1986). Without these core abilities, infants would be unable to differentiate and eventually produce complex speech sounds. It is important to track the development of auditory skills because the degree to which infants' abilities lag behind those of adults will impact directly on how infants at various ages perceive speech. In this section, the development of infants' perception of frequency and intensity is described, and it is shown that while some auditory skills mature within the first 6 postnatal months, others are still developing well into childhood.

3.2.1 Infants' Intensity Perception

In general, infants are less sensitive to sound than older children and adults as they require higher intensity (or loudness) levels in order to perceive sounds. At birth, infants' absolute thresholds (or their ability to detect sounds in quiet) exceed those of adults by approximately 30 dB at 250 Hz and 70 dB at 2000 Hz (Weir, 1976, 1979). Thus, newborn infants have greater sensitivity for low than high frequencies. At one month of age, thresholds measured via behavioural observation audiometry (BOA) are similar (e.g., Ruth, Horner, McCoy, & Chandler, 1983). However, later studies which used more sophisticated observer-based techniques to determine infant responses, obtained lower thresholds, suggesting that sensitivity at this age is approximately 35 to 45 dB worse than adults (Tharpe & Ashmead, 2001; Werner & Gillenwater, 1990). By 3 months of age, further improvement has occurred, particularly for high frequencies (Olsho, Koch, Carter, Halpin, & Spetner, 1988) and at 6 months of age, a crossover effect is observed in infants' sensitivity to the intensity of tones of different frequencies. That is, 6-month-old infants' sensitivity for low frequencies (500 Hz) is about 20 dB poorer than adults', while sensitivity for high frequencies (4000 Hz) has improved dramatically and is just 15 dB worse than that of adults (Olsho et al., 1988). Infants' sensitivity to high-frequency tones continues to mature quite rapidly throughout the next 12 months (Nozza & Wilson, 1984; Sinnott, Pisoni, & Aslin, 1983; Trehub, Schneider, & Endman, 1980) and reaches adult levels by 5 years of age (Schneider, Trehub, Morrongiello, & Thorpe, 1986; Trehub, Schneider, Morrongiello, & Thorpe, 1988). In contrast, it is not until children are around 10 years old that intensity thresholds for low frequencies reach adult-like maturity (Trehub et al., 1988).

A second aspect of intensity perception that has a bearing on how infants perceive speech is intensity discrimination or the ability to detect a change in the loudness of a sound. As with intensity thresholds, infants are worse than adults at intensity discrimination, needing larger intensity differences in order to discriminate between two tones. For example, using a 1000 Hz pure tone, Sinnott and Aslin (1985) found 7- to 9-month-old infants were able to detect an incremental (but not decremental) change in intensity ranging from 3 to 12 dB. In contrast, adults were able to detect both incremental and decremental intensity differences as low as 1 to 2 dB. Similar results have been obtained by Kopyar (1997) using tones and broadband noises, but when infants are presented with synthetic speech syllables, they perform slightly better (Bull, Eilers, & Oller, 1984). In this latter study, 5- to 11-month-old infants discriminated intensity differences as low as 2 dB. By 4 years of age, intensity discrimination (of both increments and decrements) appears to be quite mature and there is only marginal improvement between 4 and 12 years of age (Maxon & Hochberg, 1982).

3.2.2 Infants' Frequency Perception

Several aspects of frequency perception in infancy have been examined. The first of these is frequency resolution, which is a measure of the ability to detect one frequency in the presence of others. The hair cells positioned along the basilar membrane of the mature cochlea respond to progressively higher frequencies, with the lowest frequencies at the apex and the higher frequencies located in the basal region (Lasky & Williams, 2005). Thus, each position (or place) along the cochlea is associated with a particular frequency which results in a particular pattern of neural activity known as the place code. Researchers use masking studies to determine the range of frequencies that interfere with the detection of a particular frequency. If the range of masking frequencies is broad, this indicates poor frequency resolution or a lack of precision in the place code for that frequency. Impressively, 3-month-old infants demonstrate adult-like resolution for low frequencies, while for high frequencies, maturity is observed at 6 months of age (Olsho, 1985; Spetner & Olsho, 1990). The fact that frequency resolution takes 6 months to mature suggests that the auditory neural system is still undergoing development during this time. Because the place code for frequency is mature at birth (Bredberg, 1985; Pujol et al., 1991), the 6-month delay in reaching mature frequency resolution appears to occur because the transmission of signals from the cochlear hair cells to the cortex via the auditory brain stem is not yet operating efficiently (Ponton, Moore, & Eggermont, 1996).

In contrast to the early maturation of frequency resolution, frequency discrimination does not reach adult-like levels until much later. Prenatally, 35-week-old fetuses can discriminate low-frequency tones of 250 and 500 Hz, and the vowels /a/ versus /i/, a contrast largely based on low-frequency formant information (Shahidullah & Hepper, 1994). At 3 months of age, infants can discriminate low-frequency tones that differ by as little as 3%, while for higher frequencies, a slightly larger difference of 4% is required to elicit a discrimination response (Olsho, Koch, & Halpin, 1987). In a situation analogous to that described above for intensity perception (see section 3.2.1) at around 6 months of age, infants' superior performance with low frequencies gives way to the reverse pattern whereby infants' discrimination of high-frequency tones surpasses that of low-frequency tones. That is, frequency discrimination at 4000 Hz is adult-like, while differences of approximately 2 to 3% are still required for discrimination at 1000 Hz (Olsho, 1984; Olsho et al., 1987). This high-frequency superiority prevails until mature low-frequency discrimination performance is reached at around 10 years of age (Maxon & Hochberg, 1982). It is interesting to speculate whether the early development of low-frequency perception has evolved phylogenetically in response to the dominance of low-frequency information in the early auditory environment of many animals who begin life within an egg, womb, burrow, or pouch (Rubel, 1984) or whether external auditory stimulation drives the ontogenetic developmental sequence in individuals.

3.2.3 Sources of Immaturity in Infants' Auditory Abilities

The development of infants' auditory perception skills has been well documented (see Saffran, Werker, & Werner, 2006; Werner, 2007), but the physical bases which underlie infant auditory behaviour are less well understood. Both physiological and neural developments contribute to the immaturities observed in infant auditory perception, and the extent to which each of these factors contributes to the development of specific auditory abilities is not always entirely clear. For example, the source of the infant's immature intensity thresholds is usually attributed to immature sound conduction through the infant's external and middle ear (Sininger & Abdala, 1996). The infant ear is a less efficient sound conductor than that of the adult despite the fact that infants have a shorter and narrower ear canal than adults which results in greater amplification of frequencies around 5000 to 6000 Hz (Keefe, Bulen, Arehart, & Burns, 1993; Kruger, 1987). The inefficiency of the infant ear stems from the greater degree of motion in the compliant walls of the ear canal and tympanic membrane or eardrum (see Figure 1). This results in a loss of energy in the infant's external ear and hence less acoustic power is transmitted to the middle ear (Keefe et al., 1993; Keefe & Levi, 1996).

Immaturity of the auditory neural structures also plays a role in infants' elevated intensity thresholds. While neural development at the level of the cochlea is mature at birth or shortly thereafter (Eggermont, Brown, Ponton, & Kimberley, 1996; Pujol et al., 1991) the brain stem does not appear to be mature until around 6 months of age (Eggermont et al., 1996; Werner, Folsom, & Mancl, 1993, 1994). Furthermore, the central auditory system, located in the thalamus and cortex, takes many years to mature (Moore & Guan, 2001). Neural immaturities include incomplete myelination, which continues until around 4 or 5 years of age (Moore, 2002) and synaptic elimination, which involves the eradication of inactive synapses and preservation of active synapses. This is ongoing until around 12 years of age (Huttenlocher & Dabholkar, 1997). Thus, throughout infancy and childhood, the efficiency of the auditory system's transmission pathways continues to improve, and this ongoing improvement is a likely contributor to the maturation of intensity thresholds which do not reach adult-like levels until around 10 years of age (Trehub et al., 1988).

Clearly, the human auditory system is a work in progress over the course of several years. Although infants demonstrate adult-like frequency resolution by 6 months of age (Spetner & Olsho, 1990), most other auditory abilities improve during infancy and reach maturity during childhood (e.g., Maxon & Hochberg, 1982; Trehub et al., 1988). Yet despite this, infants manage to successfully perceive speech and acquire a native-language inventory, such that by 12 months, most are ready to produce their first word. The next section describes the development of infant speech perception and highlights the consistencies which exist between the development of basic auditory abilities and infants' speech perception.

3.3 Infants' Perception of Speech

To acquire language, infants must learn not only native-language segments, but also the suprasegmental features that mark the structure of their native language. Firstly, we examine how infants' suprasegmental perception develops over the first 12 months of life, and this is followed by a review of the development of infants' segmental perception.

3.3.1 Suprasegmental Information

From birth, infants are highly attuned to the suprasegmental aspects of speech. Recall that prenatally infants have good access to low-frequency prosodic speech information and in the first months of life infants' sensitivity to low frequencies is more mature than to high frequencies. Thus, it is perhaps not surprising that newborns attend initially to the rhythm and intonation of speech, preferring the exaggerated prosody of IDS to ADS (Panneton Cooper & Aslin, 1990) and relying on rhythmic information to recognise their ambient language (Mehler et al., 1988; Moon et al., 1993).

3.3.1.1 Infants' Recognition of their Native Language

One of the most salient features of human speech is its rhythm or temporal organisation. Native speakers modify loudness, pitch, and duration cues at regular intervals to create a language's characteristic rhythm (Crystal, 1969). Depending on the rhythmic unit employed, languages are classified as either stress-timed, syllable-timed, or mora-timed (Abercrombie, 1967). In stress-timed languages such as English, around 80% of disyllabic words have a strong-weak or trochaic stress pattern (e.g., *pliant*) and the rest have a weak-strong iambic pattern (e.g., *comply*) (Cutler & Carter, 1987). Dutch and German are also stress-timed, whereas languages such as Italian, Spanish and French are syllable-timed. In syllable-timed languages, equal emphasis is placed on each syllable and they occur at roughly equal time intervals, although word- or phrase-final syllables tend to be lengthened resulting in a characteristic iambic rhythm (Garde, 1968). Mora-timed languages, such as Japanese, have a rhythmic structure based on morae, which are syllable-like units comprising either a consonant plus short vowel; a single long vowel; or a syllable-final nasal or geminate consonant (Hoequist, 1983). Cutler (1994; Cutler & Mehler, 1993) claims that the rhythmic class of a speaker's native language directly influences their segmentation of the speech stream. For instance, the segmentation strategy of English-speaking adults is based on stress units, and in French speakers it is based on the syllable (Cutler, Mehler, Norris, & Segui, 1986; Mehler, Dommergues, Frauenfelder, & Segui, 1981). In order to reach this level of perceptual maturity and be able to segment the speech stream, infants must first recognise the rhythm of their native language and there is evidence that they do this at birth (Mehler et al., 1988; Moon et al., 1993).

As described in section 3.1, newborn infants can discriminate their native language from a non-native language, but only if it is from a different rhythmic class (Mehler et al., 1988; Moon et al., 1993), and they can discriminate two non-native languages if they are from different rhythmic classes (Nazzi, Bertoncini, & Mehler, 1998). By 5 months of age, infants have begun to narrow their focus specifically to the rhythmic patterns of their native language. At this age, infants can discriminate their native language from another language *within* the same rhythmic class (Nazzi et al., 2000), but are still unable to discriminate two non-native languages from their own native, or the same non-native rhythmic class (Nazzi et al., 2000). Thus, within the first 5 months of life, infants have acquired specific knowledge of their native rhythmic class and focus only on those rhythmic differences that are relevant to identifying their native language. Not surprisingly, it is also at around this age that infants first begin to show evidence of attuning more exclusively to native vowel segments (see section 3.3.2.1).

3.3.1.2 Infants' Sensitivity to Clause and Phrase Boundaries

As well as becoming more attuned to the global rhythm of their native language, infants also become increasingly sensitive to the suprasegmental cues which mark clause and phrase boundaries. Clauses and phrases are important syntactic elements of speech that infants need to identify if they are to acquire the grammatical structure of the native language (Hirsh-Pasek et al., 1987). Initially, infants perceive syntactic boundaries in a relatively universal manner, but perception becomes more language-specific as they develop. For instance, French-learning newborns are sensitive to pitch and duration cues that signal phonological phrase boundaries in another syllable-timed language, Spanish (Christophe, Mehler, & Sebastián-Gallés, 2001). By 4½ months of age, English-learning infants prefer to listen to speech with pauses inserted at natural, rather than unnatural, clause boundaries in an unfamiliar stress-timed language, Polish, but not in mora-timed Japanese (Jusczyk, 2003). However, by 6 months of age, the preference for natural clause boundaries in Polish has disappeared and is apparent only in native English (Hirsh-Pasek et al., 1987;

Jusczyk, 2003). Importantly, the preference remains when the speech stimuli are low-pass filtered at 400 Hz (Jusczyk, 1989). It is of some note also that infants show a stronger preference for natural (between-clause) over unnatural (within-clause) boundaries in prosodically exaggerated IDS, but not ADS (Kemler Nelson, Hirsh-Pasek, Jusczyk, & Cassidy, 1989). These latter studies support the claim that 6-month-olds' preference for natural clause boundaries is based on low-frequency native-language suprasegmental cues. By the time infants reach 9 months of age, they have attuned to suprasegmental cues which signal even smaller syntactic units of the native language, namely subject and predicate phrases. Jusczyk et al. (1992) showed that infants at this age prefer speech in which pauses are inserted between, rather than within, phrases and the preference is maintained in both IDS and ADS, and low-pass filtered speech.

3.3.1.3 Infants' Perception of Lexical Prosody

In addition to recognising the syntactic units of speech, infants also need to identify individual words from fluent speech, a particularly difficult task given that words are rarely separated by pauses, but occur in a continuous stream (Cole & Jakimik, 1980). From birth, there is evidence that infants can detect word boundaries using suprasegmental cues. Christophe, Dupoux, Bertoncini, and Mehler (1994) showed that French newborns can differentiate word-medial disyllables (e.g., *mati* in *grammatical*) from those constructed across a word boundary (e.g., *mati* in *coma typique*) demonstrating a sensitivity to pitch and duration differences between syllables. Furthermore, the internal prosodic structure of words is also salient for neonates. French newborns can discriminate lists of disyllabic and trisyllabic words that are equated for duration (Bijeljac-Babic, Bertoncini, & Mehler, 1993), and Italian-learning newborns distinguish between phonetically identical disyllabic and trisyllabic words which differ only in their syllabic stress patterns (Sansavini, Bertoncini, & Giovanelli, 1997). By 6 months of age, English-learning infants are starting to show that they can recognise native-language lexical items on the basis of more specific suprasegmental cues. When presented with words from English and Norwegian, a stress-timed language that is prosodically distinct from English, infants show a preference for English words, even when the word lists are low-pass filtered (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993b).

From 7½ months of age, infants' knowledge of native-language lexical prosody becomes more refined, as demonstrated by their performance in word segmentation studies. English-learning 7½ month-olds can correctly segment trochaic disyllabic words such as *donor*, but not less common iambic words such as *condone* (Jusczyk, Houston, & Newsome, 1999b). Comparable results have been obtained with French-learning infants, who only segment iambic words because that is the predominant stress pattern of French (Polka, Sundara, & Blue, 2002). Further evidence of infants' increasing familiarity with the suprasegmental structure of native-language words is found in studies showing that English-learning 9-month-olds, but not 6-month-olds, prefer to listen to English trochaic words rather than iambic words (Jusczyk, Cutler, & Redanz, 1993a).

3.3.1.4 The Shift in Attention from Suprasegmental to Segmental Information

Around 9 months of age, infants begin to show less reliance on suprasegmental cues and there emerges an ability to recognise the native language and its lexical items via segmental or phonetic information. Not surprisingly, this is precisely the age at which infants' consonantal perception begins to narrow to the native-language inventory (see section 3.3.2.2). Evidence for infants' new reliance on segmental information comes from studies with artificial languages, which show that 9-month-old infants use both rhythm and the regularity of syllable order to recognise words, whereas 6-month-olds focus only on the rhythm (Morgan & Saffran, 1995). Similarly, Jusczyk et al. (1993b) showed that 9-month-old English learners can differentiate words in English and Dutch, another stress-timed language, based solely on native-language phonotactics, that is, the rules which dictate the sequencing of segments within words. In this study, infants heard two lists of 2- and 3-syllable English and Dutch words – half the words in each list contained segments or sequences of segments not found in the other language. The results showed that English 9-month-olds, but not 6-month-olds, listened longer to the English than Dutch words. Importantly, the 9-month-old infants showed no language preference when the word lists were low-pass filtered providing support for the conclusion that the infants' discrimination was based on segmental, rather than suprasegmental, cues. Other studies show that 9-month-olds, but not 6-month-olds, prefer to listen to non-words which contain phonotactically legal (e.g., *bref*) rather than illegal (e.g., *rtum*) sequences (Friederici & Wessels, 1993); and common (e.g., *riss*) rather than uncommon (e.g., *gushe*) phonotactic sequences (Jusczyk, Luce, & Charles-Luce, 1994). Infants at this age also demonstrate awareness of the phonotactic patterns that typically co-occur with word boundaries (Mattys, Jusczyk, Luce, & Morgan, 1999). Impressively, after just 9 months of language exposure, experience-related effects have emerged suggesting that infants at this age have already acquired a relatively detailed knowledge of native-language phonotactics.

The increasing role of segmental information in infants' speech perception is also evident in word segmentation studies. As mentioned earlier (see section 3.3.1.3) English-learning 7½-month-olds are incapable of segmenting iambic words from fluent speech because they do not follow the predominant native stress pattern. When 7½-month-olds listen to sentences such as *The red guitar is brand new*, they treat the strong syllable, *tar*, as the onset of a new word, which results in them misperceiving *taris* as a word, and not *guitar*. In contrast, by 10½ months of age infants successfully segment *guitar* because they recognise the less common stress pattern and use their phonotactic knowledge to identify word boundaries. In other words, they recognise that there is a word boundary between *red* and *guitar* because they have learned that a word cannot legally begin with the segment sequence /dg/ and hence they can accept the unstressed syllable, *gui*, as the onset of a new word (Jusczyk et al., 1999b).

Another segmental cue used by infants of this age is allophony, that is, differences in the way that segments are realised depending on their position in a word. For example, a vowel is longer when it occurs in a strong syllable compared to a weak syllable; and the amount of aspiration in /t/ varies depending on its position in a word. Varying amounts of aspiration was the allophonic cue claimed to have been exploited by the infants in Jusczyk, Hohne and Bauman's (1999a) study. They found that infants at 10½, but not 9, months of age were able to differentially segment *night rates* and *nitrates* from a speech stream. Taken together, the studies described in this section demonstrate a significant shift in infants' word segmentation strategies and speech perception generally. As infants approach their first birthday, they have progressed from an early reliance on suprasegmental cues to the use of native-language segmental cues, such as phonotactics and allophony.

3.3.1.5 Theoretical Implications of Suprasegmental Speech Perception

Throughout section 3.3.1, the developmental course of infants' perception of the suprasegmental aspects of speech has been described. Infants begin by responding to the global rhythm of their native language, and over the next months their sensitivity to prosody gradually becomes more detailed and language-specific, as they gain knowledge of the suprasegmental regularities of smaller and smaller linguistic units, from tracts of speech, to clauses, phrases, and words. This shift from language-general to language-specific perception is a pattern which is repeated in the development of segmental perception – see section 3.3.2. Some researchers have suggested that infants' increasingly language-specific perception of suprasegmental information is a means of bootstrapping the identification and acquisition of native-language grammatical structures and words (e.g., Cutler, 1994; Jusczyk & Kemler Nelson, 1996). However, an alternative view suggests that, rather than rely on suprasegmental cues, infants monitor the statistical distribution and regularity of speech units (e.g., syllables) by making use of the inherent transitional probabilities in speech, that is, the fact that the syllables in a word are more likely to co-occur than syllables from two adjacent words. The classic example is *pretty baby*. The transitional probability that *pre* is followed by *ty* is higher than that of *ty* being followed by *ba*, and this latter lower transitional probability signals that a word boundary exists between *ty* and *ba* (Saffran, Aslin, & Newport, 1996). According to proponents of statistical learning models, once infants accumulate sufficient knowledge of their native language's transitional probabilities, they will be able to accurately extract words from the speech stream and there is evidence from artificial language experiments that infants can do this. Saffran et al. (1996) familiarised 8-month-olds to a series of nonsense syllables, in which the transitional probabilities between syllables were the only cues to word boundary. In the test phase, infants successfully discriminated between statistically probable and improbable words, thus demonstrating their sensitivity to transitional probabilities in speech.

As yet, the relative influence of prosodic bootstrapping and statistical learning is unknown, but it is likely both play a role, and that they interact with each other to facilitate language acquisition. For example, it has been proposed that prosodic bootstrapping creates a set of possible syllables on which statistical probabilities can be calculated (e.g., Shukla, Nespor, & Mehler, 2007), while others suggest that statistical segmentation gives rise to the lexical corpus from which infants can discover prosodic patterns (e.g., Thiessen & Saffran, 2003, 2004).

Although statistical learning is a general learning mechanism that is not specific to speech (Saffran, Johnson, Aslin, & Newport, 1999); audition (Kirkham, Slemmer, & Johnson, 2002); or even humans (Hauser, Newport, & Aslin, 2001), it is a concept that is increasingly gaining attention in many areas of infant speech perception research, and it will be explored further at the end of the next section which describes the development of infants' perception of segments. As foreshadowed above, there are consistent patterns in the development of both segmental and suprasegmental perception and these will be highlighted below.

3.3.2 Segmental Information

Although newborns' attention to speech is based on the more holistic suprasegmental aspects of speech, they also have the ability to perceive the smaller, segmental units of speech based on "innately determined universal acoustic categories" (Aslin & Smith, 1988, p.461; see also Burnham, 1986). Nearly 40 years of research shows that infants under 6 months of age can discriminate stops (Eimas, Siqueland, Jusczyk, & Vigorito, 1971); nasals (Hillenbrand, 1984); approximants (Eimas, 1975; Jusczyk, Copan, & Thompson, 1978; Karzon, 1985); certain fricatives[4] (Eilers, Wilson, & Moore, 1977); and vowels (Trehub, 1973). As early as 4 to 5 days after birth, infants can discriminate voiced stops (/b/-/d/, /b/-/g/) and vowels (/i/-/a/) when the stimuli comprise only very short CV onset bursts (Bertoncini, Bijeljac-Babic, Blumstein, & Mehler, 1987). Importantly, infants' wide-ranging discrimination ability is evident whether the speech sounds are from the native language environment (as in the studies above) or an unfamiliar non-native inventory (Bosch & Sebastián-Gallés, 2003; Lasky, Syrdal-Lasky, & Klein, 1975; Trehub, 1976; Werker, Gilbert, Humphrey, & Tees, 1981). Even more notable is the fact that young infants discriminate non-native speech contrasts that adults from the same language environment cannot. In their now classic study, Werker, Gilbert, Humprey, and Tees (1981) showed that English-learning 6- to 7-month-olds, but not English-speaking

[4] Interestingly, fricatives, which contain significant low-amplitude, high-frequency information, seem to be the most difficult for young infants to perceive, and this may be related to infants' poorer sensitivity to high-frequency sounds in the first 6 months.

adults, could discriminate two non-native Hindi contrasts (retroflex vs. dental voiceless stops /t̥/ vs. /t̪/ and voiced aspirated vs. voiceless breathy dental stops, /dʰ/ vs. /tʰ/).

Infants' universal speech perception abilities suggest that, in the earliest months, they discriminate speech sounds using a general acoustic mode of perception that relies on the acoustic differences between the sounds (Aslin & Pisoni, 1980). However, as infants accumulate experience with their native language, their previously broad-based speech perception narrows and becomes more sharply focused on the phonetic categories of the native language. This occurs in much the same way as it does with suprasegmental perception (see section 3.3.1). That is, infants' segmental perception becomes increasingly language-specific and more adult-like during the course of the first year as infants shift from their early mode of language-general perception towards one that is constrained by the sounds of the native language.

3.3.2.1 Infants' Perception of Vowels

Infants easily discriminate native and non-native vowels up to the age of 4 months (Polka & Werker, 1994; Trehub, 1976), but by 6 months there is a shift towards language-specific perception such that there is an asymmetry in discrimination performance for vowels because infants start to treat good prototypical exemplars of vowels as 'perceptual magnets'. The perceptual magnet effect was first described by Kuhl (1991) who showed that 6-month-olds discriminated a pair of non-prototypical vowels a certain distance apart from each other in F1-F2 vowel space better than a pair of vowels the same distance apart, but closer to the prototype. Thus, less prototypical vowels from the same category are regarded as more similar to the prototype vowel than to each other, even when all the vowels are equidistant acoustically (Kuhl, 1991).

Cross-language discrimination studies have also shown that infants' vowel categories are becoming organised around native-language vowel prototypes at 6 months of age. Kuhl et al. (1992) showed that American 6-month-olds perceive the English front unrounded vowel /i/ as a prototype vowel, but not the non-native Swedish rounded front vowel /y/, whereas Swedish infants demonstrate the opposite pattern, treating the Swedish /y/ as a prototype, but not the American English vowel /i/. When the native prototype vowel was used as the background stimulus, infants assimilated poor vowel exemplars into the prototype, and therefore failed to discriminate poor exemplars from the prototype. When the stimuli were reversed and a poor (non-native) vowel exemplar was used as the background, infants could discriminate the exemplars because they treat them as different vowels.

In a later study, Polka and Werker (1994) found that when English-learning infants heard two non-native German vowels, one of which was common to both English and German, and the other a vowel restricted to German, English-learning 6-month-olds showed a similar perceptual magnet effect. That is, they did not discriminate the vowels when the native vowel was the background stimulus, but did when the direction of presentation was reversed. However, the asymmetry in discrimination performance disappeared between 10 and 12 months of age as infants assimilated both vowels to a single native vowel category, irrespective of whether the native or non-native vowel acted as the background stimulus. This study shows that although infants are sensitive to native vowel categories at around 6 months of age, perceptual reorganisation for vowels continues across the course of the first year (Polka & Werker, 1994) and perhaps beyond (Polka & Bohn, 1996).

Although the perceptual magnet effect is compelling, more recent work suggests that, rather than being a language-specific effect, it is more likely a universal perceptual bias that can be modulated by language experience. In Polka and Bohn's (1996) cross-language study of non-native vowel discrimination (English: /æ/ vs. /ɛ/, German: /u/ vs. /y/) both English- and German-learning infants demonstrated perceptual asymmetry when discriminating both native and non-native contrasts. Furthermore, the asymmetry was in the same direction. For both language groups, it was the 'corner' vowel that acted as the magnet (i.e., /u/ and /æ/), irrespective of which vowel was more prototypical in each language. Thus, it is proposed that the perceptual magnet effect is not primarily an experience-related effect but rather a default setting in infant vowel discrimination in which more peripheral vowels act as magnets. The effect operates relatively independently of language experience, although language experience has been shown to affect the degree of asymmetry observed (Bohn & Polka, 2001; Polka & Bohn, 1996, 2003).

Behavioural studies of NH infants' attunement to native vowels are now being supplemented by studies of the neural correlates of vowel perception due to the advent of new brain imaging techniques. For example, a recent study used near-infrared spectroscopy to examine Japanese-learning infants' cortical responses to a phonemic short versus long vowel contrast (/a/ vs. /aː/) and a non-phonemic contrast of two vowel allophones ([a_1] vs. [a_2]) which a previous adult study had shown were discernible, although non-contrastive in Japanese (Minagawa-Kawai, Mori, Furuya, Hayashi, & Sato, 2002). The results of the infant study showed that 3- to 4-month-olds' cortical responses were almost identical whether listening to the phonemic or non-phonemic contrast. However, by 6 to 7 months of age, infants showed significantly larger responses to the phonemic contrast than the non-phonemic one. Notably, this difference was not evident at 10 to 11 months, but it re-emerged at 13 months, and was still present between 25 and 28 months (Minagawa-Kawai, Mori, Naoi, & Kojima, 2007). A second notable finding was that left-hemisphere dominance did not emerge until 13 months of age. At this age, infants showed the same pattern of cortical activity demonstrated in adult listeners, that is, a larger left-hemisphere response when listening to phonemic, than non-phonemic, contrasts (Minagawa-Kawai et al., 2002). The authors concluded that the vowel contrasts were processed by a 'generic auditory circuit' at 6 to 7 months, but after 12 months, neural processing of the contrasts becomes more linguistic.

More traditional electrophysiological techniques, such as recording event-related potentials (ERPs), have also been used to examine the neural bases of perceptual reorganisation for vowels. In these studies, mismatch negativities (MMNs) are measured, with larger MMNs indicating better discriminability. A cross-language study by Cheour et al. (1998) found that 6-month-old Finnish-learning infants exhibited similar sized MMNs listening to a non-native Estonian contrast (/e/ vs. /õ/) and a contrast native to both Finnish and Estonian (/e/ vs. /ö/). However, by 12 months of age, Finnish-learning infants' MMNs for the non-native contrast, /e/-/õ/, were consistent with those of their adult counterparts and smaller than those of Estonian infants and adults.

The neurophysiological results described above suggest that evidence of behavioural attunement to native-language vowels becomes apparent prior to the formation of stable neural correlates. Moreover, these results are consistent with studies which show that the development of native-language vowel sensitivity, although emergent at 6 months, continues throughout the first year and in some cases, may continue beyond this age (e.g., Polka & Bohn, 1996).

3.3.2.2 Infants' Perception of Consonants

It is not until around 9 months of age that the experiential effect of exposure to native-language consonants begins to become evident in infant speech perception tasks. Recall that it is at this age that there is an emerging reliance on segmental (i.e., phonotactic and allophonic) information in speech. A raft of studies shows that while 10- to 12-month-old infants maintain the ability to discriminate native consonant contrasts, the ability to distinguish previously discriminable non-native consonants is much diminished. For example, English-learning infants' ability to discriminate non-native Hindi and Salish consonant contrasts is present at 6 to 8 months but declines by 10 to 12 months of age (Werker & Tees, 1984). Similarly, English-learning 10- to 12-month-olds no longer discriminate non-native Nthlakampx ejectives (Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995) or bilabial, velar or lateral-fricative isiZulu contrasts (Best & McRoberts, 2003); and Japanese infants who could discriminate non-native /r/-/l/ at 6 to 8 months, no longer can at 10 to 12 months (Tsushima et al., 1994). As with vowels, ERP studies have revealed the neural underpinnings of perceptual reorganisation for native consonants. Rivera-Gaxiola, Silva-Pereyra and Kuhl (2005b) showed that MMNs (i.e., neural discrimination indices) are present when English-learning 7-month-olds listen to a native stop contrast (/t^ha/ vs. /da/) *and* a non-native Spanish consonant contrast (prevoiced /da/ vs. voiceless unaspirated /ta/). However, at 11 months, MMNs are present only for the native contrast.

The above studies suggest a straightforward developmental process in which an infant's immersion in a particular language environment results in a transformation in their mode of speech perception from language-general to language-specific. But the tale of attunement to native language consonants is not that straightforward. As more studies are conducted with non-native contrasts, it has become clear that there is no guarantee that contrasts that are not part of an infant's native inventory will decline in discriminability. Best, McRoberts, and Sithole (1988) reported that English-learning infants aged up to 14 months are still able to discriminate Zulu clicks, and English-speaking adults also showed no difficulty discriminating this contrast. These findings led Best and colleagues to suggest that some sounds are located outside the native-language phonological space and are therefore non-assimilable and remain discriminable even by adults. Similarly, there is no decline in English-learning infants' ability to discriminate /p'/ versus /t'/ (a bilabial versus alveolar ejective stop from Tigrinya) between 6 and 10 months of age (Best & McRoberts, 2003). The authors suggest that these two consonants continue to be discriminable by infants from a non-Tigrinya language background because they are produced by different articulatory organs (lips vs. tongue tip).

Our understanding of the effect of language environment on the development of consonantal perception has been illuminated further by a number of studies which show that the native language can have a facilitatory, not just a maintenance, effect on infants' discrimination of native speech contrasts. That is, while earlier studies suggested that exposure to the native language resulted in perceptual maintenance throughout infancy and into adulthood for native contrasts (e.g., Werker et al., 1981; Werker & Tees, 1984), more recent studies have revealed that discrimination performance for some contrasts actually improves as the infant gets older (Kuhl et al., 2006; Polka, Colantonio, & Sundara, 2001). Polka et al. (2001) showed that discrimination performance on an English contrast, /d/-/ð/, improved between 10 to 12 months of age and adulthood. The authors suggest that this is because the contrast contains short, 'acoustically weak' sounds which infants may find difficult to perceive. They also note that /ð/ occurs most often in English function words such as *the* and *that* which are known to be less salient for infants (Shi & Werker, 2001), and therefore, early perception of the phoneme /ð/ may not be as good as that of other phonemes which occur more regularly in content words.

3.3.2.3 Theories of Infants' Segmental Perception

Taken together, the results discussed in section 3.3.2 suggest that the influence of the native language interacts with the acoustic and articulatory differences between speech sounds to influence the developmental trajectory of particular speech contrasts. In developing theories to account for this, researchers have proposed different models. Best's (1995; Best & McRoberts, 2003) Perceptual Assimilation

Model (PAM) states that infants (and adults) directly perceive segments as articulatory gestures, which vary in the degree to which they match native categories. As infants accumulate experience with their native language, robust native categories develop and perceptual performance will depend on how well infants perceptually assimilate sounds into these categories. If a contrast contains two sounds that are easily assimilated into two separate native categories, then discrimination performance will be good. However, if two segments fall within the one category, then discrimination performance is likely to be poor, depending on the relative 'goodness of fit' of each sound to the category. In addition to the concept of 'category goodness', PAM also states that the discriminability of sounds will depend on the extent to which they differ in terms of articulation. Segments produced by the same articulatory organ are predicted to be more difficult to discriminate than those produced by different articulatory organs.

An alternative theoretical account has been developed by Kuhl (2004; Kuhl et al., 2008) whose Native Language Magnet (NLM) model states that native language experience 'warps' perception such that frequently heard sounds form native-language prototypes. These prototypes then act as 'magnets' drawing in less-prototypical exemplars and making them perceptually similar to the prototype, whereas the perception of non-native/non-prototypical sounds declines due to a lack of exposure. In the recently expanded version of the model (NLM-e), Kuhl incorporates the concept of statistical learning into her model to explain how native-language prototypes are formed (Kuhl et al., 2008). Infants are said to track the distributional frequencies of phonetic units in speech and the patterns that emerge form the basis of the prototypes. Take, for example, an infant in an English-language environment. The infant would hear bilabial stops on a regular basis and although there is great deal of variation in how these exemplars are produced, the majority of the bilabial stops heard would be either voiced [b]s from one end of the VOT continuum or voiceless [p]s from the other end of the continuum, with few exemplars falling between these two endpoints. Thus, the English-learning infant would detect the two-way (or bimodal) distribution of bilabial stops and form two corresponding bilabial stop prototypes. Evidence that infants can track phonetic distributions, and that their perception is altered accordingly, comes from studies by Maye and colleagues (Maye, Weiss, & Aslin, 2008; Maye, Werker, & Gerken, 2002). They showed that, with less than 3 minutes of exposure to a uni- or bimodal distribution of stop consonants, those infants that had been exposed to the bimodal distribution successfully discriminated the contrast, while those exposed to the unimodal distribution did not.

Another defining aspect of Kuhl's model is the assertion that infants' experience with the native language and the tracking of its statistical regularities results in physical changes in the brain. Kuhl claims that over time, neural networks become 'committed' to the phonetic patterns of the native language and infants' increasingly language-specific speech perception reflects a strengthening of the relevant neural connections. Uncommitted neural circuitry, on the other hand, underlies infants' declining ability to perceive non-native speech contrasts (Kuhl, 2004; Kuhl et al., 2008). Evidence for neural commitment comes from adult brain imaging studies which show that, when listening to non-native sounds, brain activation is less efficient and occurs over a wider spatial area than when perceiving native sounds (Zhang, Kuhl, Imada, Kotani, & Tohkura, 2005). In NLM-e, the concept of neural commitment has been developed further with the prediction that stronger native-language neural commitment during infancy will result in better language abilities in later childhood. A recent ERP study showed that 7½-month-olds, who discriminated native sounds better than non-native sounds as measured by larger MMNs, also scored higher on tests of language ability between 14 and 30 months of age than infants who showed the reverse pattern of neural commitment, that is, larger MMNs for non-native than native contrasts (Kuhl et al., 2008).

3.3.3 Conclusion

Despite differences in the proposed mechanisms claimed to underlie the development of infants' speech perception, all models are predicated on the fact that infants' increasing experience with the native language is a major factor in determining how infants perceive speech. This chapter has outlined how infants emerge from the safety of their relatively quiet, low-frequency fetal environment into the vast and noisy world of spectrally complete spoken language, experienced for the most part in the form of IDS, with its incumbent prosodic exaggerations. Equipped with their superior low-frequency sensitivity, infants respond first to the rhythm and intonation of speech and perceive spoken language in a language-general acoustic mode. By 6 months of age, infants are more sensitive to high-frequency sounds and their experience with the native language starts to have a profound effect on their perception of speech, especially vowels. By 9 months of age, perception of vowels and consonants becomes more language-specific and infants start to focus more on segmental than suprasegmental information in readiness for reaching their first major linguistic milestone: uttering their first word. Thus, both perceptually and productively (see chapter 2), the language of NH infants becomes increasingly language-specific. The next two chapters examine evidence from infants with HL and detail how impoverished native-language exposure leads to impaired language development.

CHAPTER 4

HEARING IMPAIRMENT IN INFANCY

This chapter describes how HL is diagnosed and treated in infancy, with a particular focus on systems and processes in Australia.

4.1 Newborn Hearing Screening

Each year in Australia, permanent bilateral HL (greater than or equal to 40 dB in the better ear) is observed in around 1.1 per 1,000 live births, which equates to around 300 babies (Ching et al., 2007). The incidence of HL in Australia is comparable to the identification rates observed in the US (Mehl & Thomson, 2002) and UK (Fortnum, Summerfield, Marshall, Davis, & Bamford, 2001). Most infants with a permanent bilateral HL are identified in the first few days of life through one of the state-based newborn hearing screening programs. In 2000, Australia's first large-scale newborn hearing screening program commenced in five maternity hospitals in Perth (Coates & Gifkins, 2003). Today, newborn hearing screening programs are in place in all states and territories of Australia, with varying levels of coverage. Programs in New South Wales (NSW), South Australia (SA), Queensland and the Australian Capital Territory cover more than 95% of all births (considered full coverage). Tasmania's program reaches approximately 80% of new births, Victoria's approximately 57%, and Northern Territory's only 7%, but there are plans in place to achieve full coverage in each of these jurisdictions within the next few years. Paradoxically, Western Australia (WA), the state in which screening was first introduced, has a coverage rate of only 43% and is yet to make a firm commitment to expand its initial program (Glennon, 2008).

Although newborn hearing screening is widely implemented both in Australia and internationally, it is not universally supported. There is no doubt that screening programs have significantly reduced the age at which HL is diagnosed (e.g., Durieux-Smith & Whittingham, 2000; Kennedy, McCann, Campbell, Kimm, & Thornton, 2005), but some are opposed to screening because they believe it can lead to unnecessary anxiety when false positive results occur (Bess & Paradise, 1994; Paradise, 1999). However, evidence suggests that of those families whose children were falsely diagnosed, few experienced elevated levels of anxiety, and when they did, it was short-lived and accompanied by a prevailing positive attitude to newborn hearing screening (Young & Andrews, 2001). Detractors of newborn hearing screening have also suggested that it is sufficient to screen only those infants who are classified as having a 'high risk' of hearing impairment because this approach will identify the majority of HI cases (Bess & Paradise, 1994; Paradise, 1999). However, approximately half of all HI children do not fall into the established 'high risk' categories (Durieux-Smith & Whittingham, 2000) and therefore, without a screening program, diagnosis of these infants would most likely occur closer to two years of age, the typical age of diagnosis prior to the introduction of widespread screening (Hyde, 2005). A complete discussion of the relationship of newborn hearing screening to early diagnosis, intervention and associated language and speech outcomes can be found in chapter 5.

Most screening programs in Australia use an automated auditory brain stem response (ABR) procedure to screen for HL. Put simply, the ABR tests whether the brain responds to external auditory stimuli. When infants are asleep or otherwise quiet and still, electrodes are attached to the head to record the electrical activity in the auditory pathway while sounds of different frequency and intensity are played through headphones or via an ear canal probe. The EEG responses obtained are automatically averaged and then compared to a template, resulting in either a 'pass' or 'refer' result (Coates & Gifkins, 2003). In the SA and WA programs, the ABR test is used in conjunction with an otoacoustic emissions (OAE) procedure (Glennon, 2008). This procedure is quicker to administer than the ABR procedure and tests the functioning of the cochlea's outer hair cells. Wideband clicks are played through a probe inserted in the ear canal and the acoustic energy produced by the hair cells in response to the stimuli is recorded. As in the ABR test, an automated device returns a 'pass' or 'refer' result (Coates & Gifkins, 2003). While neither the ABR nor OAE are direct tests of hearing, they are effective screening tools because they are objective tests which can be administered quickly and by non-audiologists. If a 'refer' result is obtained, infants undergo comprehensive audiological testing to determine whether a HL is present and whether hearing aids or cochlear implants are indicated.

4.2 Assessment and Treatment of Hearing Loss in Infancy

In order to gain a more complete hearing assessment of young infants with a suspected hearing loss, pediatric audiologists complement the initial electrophysical test results used in newborn hearing screening with behavioural tests such as BOA. Although the human ear can detect frequencies between 20 and 20,000 Hz, audiological tests concentrate on the frequency range between 250 and 8000 Hz, as this is the range in which most speech sounds occur (Gelfand, 1998). BOA is a technique in which the audiologist produces a range of environmental sounds using items such as rustling cellophane, rattles, bells, and bicycle horns. The sounds produced are either low, mid, or high frequency and the loudness of each sound is recorded using a sound level meter. The infant, who is ideally in a 'light' sleep, is observed to see if they respond when the sounds occur. Possible responses include startling, particularly in response to a loud noise; moving or looking towards the sound; or the cessation of sucking when a sound is heard. Once infants are able to control their head movements at around 6 months of age, audiologists use visually reinforced orientation audiometry (VROA) to assess hearing. In this method, infants are trained to turn their head towards a loudspeaker when a sound is heard. Correct head turns are reinforced by the appearance of a visual display or reward, often a puppet accompanied by bright flashing lights. Using VROA, it is possible to obtain accurate hearing thresholds across the frequency range, and if insert earphones or headphones are worn, thresholds for each ear can be obtained. From around 2½ years of age, children's hearing can be tested using conventional pure-tone audiometry, albeit in a 'play' setting.

Most cases of HL in infancy are sensorineural losses, that is, either the cochlea or the auditory nerve is impaired. The impairment may be caused by genetic factors, viral infections, complications arising from a premature or traumatic birth, or the effect of certain drugs (Roizen, 1999). A sensorineural HL results in a range of hearing deficits:

- reduced audibility – some sounds will be completely inaudible, while others may be partially inaudible because only part of their spectra can be heard;
- smaller dynamic range – the gap between what is audible and what is intolerably loud is reduced;
- impaired frequency resolution – it is difficult for the HI listener to detect and discriminate sounds of different frequencies; and
- diminished temporal resolution – HI listeners find it difficult to hear sounds in rapid succession (Dillon, 2001).

In contrast, a conductive HL results only in the attenuation of sound (Dillon, 2001), and is caused by a blockage in, or damage to, the outer or middle ear, often as a result of wax or fluid associated with chronic otitis media. In many cases, a conductive HL may be improved by surgical treatment.

Regardless of the HL type, audiologists use hearing thresholds to define the degree of HL. When hearing thresholds occur between 21 and 45 dB, this is termed a mild loss, 46 to 65 dB is classified as moderate, 66 to 90 dB severe, and 91+ dB profound. In Australia, infants diagnosed with a profound HL, and for whom hearing aids are of little or no benefit, are candidates for cochlear implants. This group comprises about 11% of all HI infants (Ching et al., 2007). Infants with mild, moderate and severe losses are referred to Australian Hearing (an agency of the Australian government) so that hearing aids can be fitted. Fitting infants with hearing aids is not a straightforward exercise. In addition to practical considerations arising from clients who are given to wriggling and sleeping at inopportune times, infants' ears grow at a rapid rate and in the first 2 years, new earmolds are required every few weeks.

Another significant challenge is to address the acoustic effects of the smaller size and different shape of the infant's ear canal. The newborn infant's ear canal has a high resonance frequency (Kruger, 1987) which does not reach lower adult-like values until around 2 years of age. This means that an infant's ear canal receives higher levels of sound than an adult's from the same input, especially at higher frequencies (Seewald & Scollie, 1999). This has implications for both the initial assessment of infants' HL (as described above) and for determining the appropriate level of hearing aid gain. When infants' hearing thresholds are measured in preparation for a hearing aid fitting, the thresholds must be adjusted to account for the resonance characteristics of infant ears. Similarly, when the output level of infants' hearing aids is verified using a coupler (which is based on the volume of an adult ear canal), an additional measure must be taken: the real-ear-to-coupler difference (RECD), via which the audiologist can ensure that amplification is at the correct level for the particular infant (Dillon, 2001; Scollie, 2006). Ensuring the correct level of amplification is particularly important for infants because, unlike adults and older children, they are unable to tell us if sounds are too soft or too loud and cannot adjust the volume on their hearing aids. Audiologists need to ensure that excessive amplification is avoided so that any residual hearing infants may have is not damaged by their hearing aids. Equally, it is important that amplification is not underestimated as speech sounds need to be sufficiently audible to facilitate language acquisition (Ching, 2003; Stelmachowicz, 2000).

4.3 Pediatric Amplification Methods

Although several different methods are available for amplifying speech through hearing aids, there are two that are most widely used, particularly with children. The first of these is the NAL-NL1 (National Acoustic Laboratories – Nonlinear Version 1) formula (Dillon, 1999). The original version of the formula has undergone several revisions since it was first published (Byrne & Tonisson, 1976), but the philosophy behind the approach remains the same: to provide different levels of amplification across the speech spectrum such that speech intelligibility is maximised while maintaining a 'normal' level of loudness, that is, a loudness level "similar to that perceived by a NH person listening to the same sound" (Ching, Britton, Dillon, & Agung, 2002, p. 12).

The NAL-NL1 method prescribes frequency responses by way of a complex formula which takes into account:

- The spectral shape of normal speech which is also known as the long-term average speech spectrum (LTASS). When the frequency and amplitude (or loudness) characteristics of continuous speech are averaged over time, speech has an intrinsic negative spectral tilt of between -3dB and -5dB/octave above 800 Hz (Byrne et al., 1994). That is, the low-frequency components of speech are louder than the high-frequency components, and from 800 Hz upwards the amplitude of the components decreases by about 3 to 5 dB every time the frequency doubles (see left panel of Figure 2).

- The relative importance of different frequency regions to intelligibility. For instance, the low-frequency parts of speech are prescribed less gain because they have been shown to contribute least to speech intelligibility in adults (Dillon, 2001).
- The shape of the normal loudness curve. At any input level and frequency, the gain is adjusted so that the loudness is the same as that which would be perceived by a person with NH.

Thus, for most hearing losses, NAL-NL1 prescribes a generally positive frequency response because it gives speech the spectral balance that results in maximum intelligibility and normal overall loudness (Dillon, 2001). For infants and children, the standard NAL-NL1 fitting procedure is adapted to incorporate the RECD procedure described above.

The other widely used fitting method is the DSL m[i/o] (Desired Sensation Level multistage input/output) version 5.0 (Scollie et al., 2005) originally developed for the pediatric population in the early 1980s (Seewald, Ross, & Spiro, 1985). In contrast to NAL-NL1, the DSL method aims to provide maximum audibility across all frequencies "so that phonemic patterns can be learned" (Seewald, Moodie, Scollie, & Bagatto, 2005, p. 149). Despite the fundamentally different approaches inherent in each of these methods, both of them preserve the natural loudness balance between low- and high-frequency regions and the frequency responses that each prescribes are similar in shape for a wide range of audiograms (see Figure 2, right panel; Seewald et al., 2005). Greater differences are observed for more severe-profound sloping HLs. In these cases, NAL-NL1 provides *less* gain for high-frequency sounds because research suggests that as HL becomes more severe, too much audibility in the high frequencies is of little benefit (Ching, Dillon, & Byrne, 1998) and may be detrimental to speech intelligibility (Hogan & Turner, 1998). DSL5.0, on the other hand, focuses on providing habilitative audibility of all frequencies (Seewald et al., 2005) and therefore when dealing with a HL that is more severe at the higher frequencies, it will provide *more* gain as the frequency increases (Dillon, 2001).

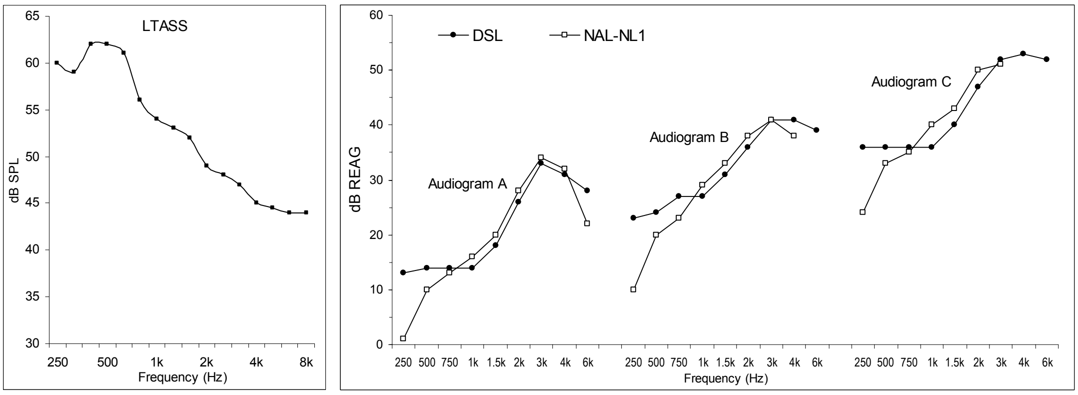

Figure 2. The LTASS in hearing aid prescriptions.
Left panel: The LTASS shows that lower frequencies have higher intensity than high frequencies (adapted from Byrne et al., 1994 with permission). Right panel: Comparison of NAL-NL1 and DSL4.1 prescriptions for three audiograms: A) mild-moderate sloping HL; B) moderate sloping HL; and C) severe sloping HL (adapted from Seewald et al., 2005 with permission).

4.4 Early Intervention Programs

Families of newly diagnosed infants (whether fitted with hearing aids or cochlear implants) are provided with information about early intervention programs. In NSW, most HI infants attend early intervention programs provided free of charge by charitable organisations such as The Shepherd Centre, St Gabriel's School for Hearing Impaired Children, and Royal Institute for Deaf and Blind Children. These three major centres operate primarily under the principles of auditory-verbal therapy, a method which makes use of children's residual hearing to perceive speech and develop spoken language. Parents are integral to the success of the auditory-verbal approach and work with the therapist to set appropriate communication goals for their child. Infants and parents attend weekly sessions with an auditory-verbal therapist, but parents are the main proponents of the therapy as they communicate with their children on a daily basis and are encouraged to provide as many opportunities as possible for their children to listen and speak. These centres also provide assistance with preschool placements and ongoing support when children make the transition to school. Many children with HL now attend mainstream schools. In Australia, it is estimated that around 85% of students with significant permanent HL attend regular schools, usually with additional support from teachers of the deaf (Punch, Creed, & Hyde, 2005).

The large numbers of HI children enrolled in mainstream schools is testament to the success of newborn screening and early intervention programs. However, as the next chapter describes, in the years prior to widespread newborn hearing screening, adverse language and educational outcomes for HI children were commonplace.

CHAPTER 5

OUTCOMES FOR HEARING-IMPAIRED INFANTS

This chapter describes how outcomes for HI infants have improved over the past decade. The first part of the chapter describes the language and educational outcomes for late-identified HI children, followed by a discussion of the progress that has been made as a result of newborn hearing screening. Despite these improvements, outcomes for HI children are still not on par with those of NH children. Thus, the second part of the chapter reviews research showing how outcomes for early-identified children could be improved further and introduces the rationale for the current study.

5.1 Outcomes for Late-identified HI Infants

Before the advent of widespread newborn hearing screening, the average age of HL identification in Australia and the US was between 18 and 36 months (Mace, Wallace, Whan, & Stelmachowicz, 1991; Robertson et al., 1995). Studies conducted on this late-identified HI cohort show that language and educational outcomes are severely compromised compared to those of NH children (Allen, 1986; Blamey et al., 2001; Davis, Elfenbein, Schum, & Bentler, 1986). Delays in spoken language production emerge during infancy: late-identified infants with a profound HL start producing canonical babble later than NH infants, often not until the second year of life (Eilers & Oller, 1994; Oller & Eilers, 1988). Moreover, the babble of HI infants differs from that of NH infants, with fewer canonical syllables and a smaller range of consonants (Nathani, Oller, & Neal, 2007; Stoel-Gammon & Otomo, 1986); higher and more variable F0 (Kent, Osberger, Netsell, & Goldschmidt Hustedde, 1987); and shorter utterances containing more unvoiced sounds (Clement, Koopmans-van Beinum, & Pols, 1996).

Beyond infancy, speech production of HI children shows further signs of delay. For example, at the age of 3 years, late-identified HI children produce less speech during free play than NH 2-year-olds (Lederberg & Everhart, 1998) and HI children's speech is less intelligible than that of NH peers. The speech of children with severe-to-profound HL is rated as intelligible only around 20% of the time, although there is considerable variation within this group (Carney, 1986) and better intelligibility ratings are correlated with less severe losses (Elfenbein, Hardin-Jones, & Davis, 1994). Poor intelligibility is particularly problematic for HI children because it is closely associated with how their cognitive competence is perceived by other listeners (Most, Weisel, & Lev-Matesky, 1996). Receptive language skills of HI children are also delayed compared to those of NH peers (Geers & Moog, 1989), and lexical/semantic and syntactic/morphologic skills are significantly impaired in this population (Moeller, Osberger, & Eccarius, 1986). By the time late-identified children reach high school at around 12 years of age, the average language delay is approximately 4 to 5 years (Blamey et al., 2001). After the age of 12 or 13 years, there is little improvement in language skills and the gap between HI and NH children widens. By the time late-identified HI children graduate from high school, the delay is severe, with language competencies equivalent to those of NH children aged around 10 years younger (Moeller et al., 1986). With the advent of newborn hearing screening and earlier identification of hearing impairment, outcomes for HI children have vastly improved. This topic will be explored in the next section.

5.2 Outcomes for Early-identified HI Children

5.2.1 Early Identification versus Late Identification

Research into the efficacy of newborn hearing screening and early identification is starting to accumulate. Robinshaw (1995) reported some of the earliest evidence that an early diagnosis is advantageous for HI children. A study of the gestural and vocal communication of five HI children identified before 6 months of age showed that language skills developed at a similar rate to NH children and well before that of late-identified children. Similarly, Apuzzo and Yoshinaga-Itano (1995) found that 40-month-olds who had been identified before 3 months of age had higher language scores than those diagnosed after 3 months of age. In a subsequent much larger study, which became a landmark in support of universal newborn hearing screening, Yoshinaga-Itano, Sedey, Coulter, and Mehl (1998) reported that toddlers between 1 and 3 years of age, who had been identified with a HL before 6 months of age and enrolled in the Colorado Home Intervention Program (or a similar program) shortly thereafter, had significantly higher expressive and receptive language scores than those identified after 6 months. Further studies of Colorado infants with HL (aged between 9 months and 5 years) confirmed that those who underwent hearing screening in hospital (84% of whom were diagnosed prior to 6 months of age) achieved higher expressive and receptive language scores than matched unscreened infants. Of the screened infants, 76% achieved language scores within the normal or borderline-normal range, compared to only 32% of unscreened infants. In observational analyses of the infants' speech production, screened infants' speech was rated as more intelligible, and included more consonants and more consonant blends than that of unscreened infants (Yoshinaga-Itano, Coulter, & Thomson, 2000, 2001).

In the studies conducted by Yoshinaga-Itano and colleagues, language scores were obtained by asking parents to complete relevant parts of the Minnesota Child Development Inventory. A study which assessed the vocabulary and verbal reasoning skills of HI 5-year-olds using the Peabody Picture Vocabulary Test and Preschool Language Assessment Instrument also found higher language scores for early-identified children (Moeller, 2000). Those children who had been enrolled in an intervention program by the age of 11 months (83% of whom were identified prior to 6 months) had significantly higher language scores than infants who began intervention later, and the difference between early- versus late-starters was further exacerbated when late-starters had only limited family involvement in intervention.

Despite these initial studies showing a consistent positive link between early diagnosis and intervention and language outcomes, several more recent studies of older HI children have produced mixed results with regard to the long-term benefits of early diagnosis and intervention. An Australian population-based study found that the language ability of HI children aged 7 to 8 years was not related to age of identification (which ranged from 1 to 53 months), but was related to severity of HL (Wake, Poulakis, Hughes, Carey-Sargeant, & Rickards, 2005). In a similar population-based study conducted in the UK, Kennedy et al. (2006) found that 7- to 8-year-old HI children, identified before 9 months of age, had better expressive and receptive language skills than those identified after 9 months, but there was no significant difference in speech intelligibility or fluency between the groups. A Canadian study by Fitzpatrick, Durieux-Smith, Eriks-Brophy, Olds and Gaines (2007) found no differences in the oral communication of children aged between 2 and 5 years who were identified before 12 months and those identified later. As in the Australian study, severity of HL, but not age of identification, was associated with communication outcomes, that is, the greater the HL, the lower the communication scores.

There are various factors which may have contributed to the less promising results of these recent studies compared to those of earlier studies. Firstly, the later studies use 9 and 12 months rather than 3 and 6 months as the cut-off point for early versus late diagnosis. It may be that only very early diagnosis which arises from universal newborn hearing screening has a significant effect on language outcomes. A second possibility is that there has been a general improvement in access to amplification, cochlear implantation, and intervention services, which may have reduced some of the adverse effects of late identification. Thirdly, language outcomes in most of the later studies are assessed in school-aged children, rather than preschoolers. It might be the case that the positive effects of early diagnosis are not sustained as children reach school age and instead, as Wake et al. (2005) and Fitzpatrick et al. (2007) found, severity of loss takes over as the dominant factor affecting language outcomes. Indeed, a Belgian review of educational and language outcomes for 229 children identified with a HL through newborn hearing screening found that although 85% of screened children with no additional disabilities were in mainstream schools by the age of 5½ years, in terms of language development, across the whole sample, only 34.5% of children fell within the normal range, with severity of HL and additional disabilities impacting significantly on language delay (Verhaert, Willems, Van Kerschaver, & Desloovere, 2008).

5.2.2 Early Identification versus Normal Development

On balance, a review of the available evidence suggests that newborn hearing screening and the associated early diagnosis of HL result in language and educational outcomes that are superior to those of late-identified children (Nelson, Bougatsos, & Nygren, 2008). However, it appears that early-identified children's development of spoken language could be further improved because it is still delayed compared to that of NH peers. For example, early-identified HI children, who also receive early amplification and intervention, begin to produce consistent canonical babble approximately 6.5 months later than NH children (Moeller et al., 2007b). A similar delay is found in early-identified HI children's acquisition of vowels, stops, nasals, glides, and liquids, which occurs approximately 7 months later than in children with NH. In their babble, HI children produce fewer complex multisyllabic utterances and more vowel-only utterances than their NH peers (McGowan, Nittrouer, & Chenausky, 2008; Moeller et al., 2007b; von Hapsburg & Davis, 2006). Their consonant inventories are also smaller (Moeller et al., 2007b; Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004), and they produce fewer coronal consonants and more bilabial consonants than age-matched NH infants (McGowan et al., 2008; von Hapsburg & Davis, 2006). It is possible that the prevalence of bilabial consonants results from HI infants' early reliance on visual rather than auditory perception (von Hapsburg & Davis, 2006). Moreover, at 24 months, early-identified HI children's word production is found to be less accurate, less recognisable, and less complex than that of NH peers (Moeller et al., 2007a).

The differences in the productions of HI and NH infants outlined above were observed in age-matched infants. Given that HI infants' average age of amplification ranged from 2.2 to 4.9 months in these studies, it is likely that the differences between NH and HI peers arise at least partly because early-identified HI infants have been deprived of auditory stimulation for approximately 3 months in utero and for the period between birth and the fitting of amplification. Thus, it is not surprising that language development is delayed when age-matched controls are used. When HI children were compared to NH children on the basis of whether or not they had reached the canonical babbling stage, rather than on the basis of age, there were no significant differences between the phonetic inventories of the two groups (Moeller et al., 2007b). Similarly, as the NH and HI children reached later stages of language development, fewer differences were found than in the NH versus HI age-matched comparisons. Thus, it seems that, while language development may be delayed in early-identified HI children, it is not fundamentally different to that of NH peers.

One exception to the above findings is in the area of fricative/affricate production, where it seems that HI infants' language development does differ markedly from both age-matched and experience-matched NH infants. It has been found that early-identified 12- to 16-month-olds have a smaller fricative inventory (Stelmachowicz et al., 2004) and produce proportionally fewer fricatives (McGowan et al., 2008) than their NH counterparts. Even when matched for vocal stage, HI infants produced fewer fricatives than NH infants (Moeller et al., 2007b). Furthermore, while NH infants steadily increase their use of fricatives and affricatives between 10 and 24 months of age, HI infants' fricative/affricative production shows very little change over this period (Moeller et al., 2007b). This pattern is significantly different from that observed for all other consonants and vowels, production of which increases at a similar rate for both NH and HI infants. It has been suggested that HI infants find fricatives difficult to perceive and consequently produce because these low-amplitude, high-frequency sounds are not well amplified by current hearing aids (Moeller et al., 2007b; Stelmachowicz et al., 2004).

Findings which show that speech production is delayed in early-identified HI infants and toddlers imply that these infants' speech *perception* is also delayed or impaired to some extent. However, there have been very few studies of speech perception in young HI infants. An exception is a study by Polka and Rvachew (2005) which showed that a history of otitis media, and therefore a higher likelihood of intermittent conductive HL, impacts negatively on infants' discrimination of speech sounds between 6 and 9 months of age. The scarcity of speech perception studies of infants with sensorineural HL is to be expected because the widespread detection of HL in infancy is only a relatively recent development. It is only in the last 5 to 10 years that it has been possible to identify and study HI babies during infancy. Now that universal newborn screening is widespread, there is an opportunity to fill this gap in the research and study speech perception in this population.

Recognising the difficulties inherent in assessing speech perception in young HI infants, Eisenberg, Martinez and Boothroyd (2007) have tested a number of research paradigms for this purpose. Preliminary results show that from 6 months of age, hearing-aided infants and toddlers with a HL ranging from mild to profound can complete a speech discrimination task using a visually reinforced conditioned head turn (CHT) procedure, and they perceive vowel contrasts better than consonant contrasts (Martinez, Eisenberg, Boothroyd, & Visser-Dumont, 2008). Using a similar procedure, researchers at the University of Colorado have reported that HI infants fitted with hearing aids and cochlear implants show progressive improvement in native-language discrimination performance and that vowel contrasts are mastered earlier than consonant contrasts. (Fredrickson & Uhler, 2006; Uhler, Fredrickson, Gabbard, & Yoshinaga-Itano, 2007; Yoshinaga-Itano, 2007b). Interestingly, Yoshinaga-Itano has speculated that the visual reinforcement task, although designed to assess perception, might also serve as a training exercise as the infants show significant improvement during test sessions and from one session to the next. It may be that the repeated presentation of minimal pairs during the task has the effect of directing the infant's attention to the critical acoustic cues that differentiate native-language phonemes (Yoshinaga-Itano, 2007a, 2009).

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5.3 Beyond Early Identification

5.3.1 Improving Language Outcomes

The studies described in the previous section (5.2.2) show that early identification of HL and prompt amplification and intervention are not sufficient to achieve a rate of language development that is truly on par with normal development. Hence, researchers and practitioners must look to other pieces of the puzzle which might be improved in order to boost language outcomes for HI children. Considerable variability in the linguistic performance of early-identified HI children suggests that there must be a number of variables that contribute to how well spoken language develops in this population. For example, consistency of hearing aid use, type of intervention, level of family involvement, and type of amplification are all contributing factors which influence the quality and quantity of a child's auditory experience and which, in turn, are likely to impact on language outcomes. The focus of the current research is on the type of amplification provided through infants' hearing aids.

5.3.2 Rationale for the Current Study

As already described, speech has a natural spectral slope of -3 to -5 dB/octave above 800 Hz (Byrne et al., 1994). This means that low-frequency speech sounds are relatively loud, whereas higher frequency sounds are less intense. Infants' hearing aids are most commonly fitted using either the NAL-NL1 or DSL [i/o] prescriptions, which are also widely used for older hearing aid recipients. Both of these fitting methods preserve the natural loudness balance between low- and high-frequency regions and thus, to an extent, maintain the natural shape of the speech spectrum. However, because infants are in the midst of acquiring the details of native-language vowels and consonants, they are unlike other hearing aid users and might benefit from an alternative amplification strategy. For example, infants might benefit from amplification in which the speech spectrum is positively tilted to emphasise the high frequencies, or negatively tilted to boost the intensity of the low frequencies.

To explore the type of amplification that is most suitable for infants acquiring language, it was critical to first examine how the perceptual systems of NH infants' respond to speech sounds in which the spectral profile has been tilted. Thus, the aim of this research was to provide knowledge of how NH infants' discrimination ability is affected when different spectral tilts are applied to consonants and vowels. The next chapter outlines the study and provides the reasoning behind the spectral tilt modifications, speech contrasts and infant ages.

CHAPTER 6

THIS STUDY

The aim of this study was to examine NH 6- and 9-month-olds' discrimination of three speech contrasts: high-frequency fricatives, mid-frequency approximants and low-frequency vowels under three spectral tilt conditions: unmodified normal speech; positive tilt (high-frequency emphasis); and negative tilt (low-frequency emphasis). This chapter contains a review of literature pertaining to infants' perception of spectral shape, spectral tilt in tonal complexes, and more recently, spectral tilt applied to speech. This is followed by a description of the spectral tilt modifications, speech contrasts, and infant ages used in this study. Finally, the predicted outcomes of the study are presented.

6.1 Spectral Tilt

6.1.1 Infants' Perception of Spectral Tilt

The little research that has been conducted on infants' perception of spectral tilt has mostly examined it from the point of view of infants' perception of timbre. The notion of timbre is relevant to both speech and music as timbre is the quality which characterises different instruments, and it also plays a role in differentiating speech sounds and voices. Differences in timbre arise because of differences in energy distribution across a spectrum. For example, middle C played on a tuba and a flute with equal loudness and duration will differ in sound quality (or timbre) because the frequency components of which they are comprised have different levels of intensity, that is, the sounds differ in spectral shape. Similarly, in the case of speech, two vowel sounds may be uttered with the same pitch, loudness, and duration but will be heard as different vowels, for example, /i/ and /ɐ/, because they are comprised of frequencies of varying energy or intensity. These examples are shown in Figure 3.

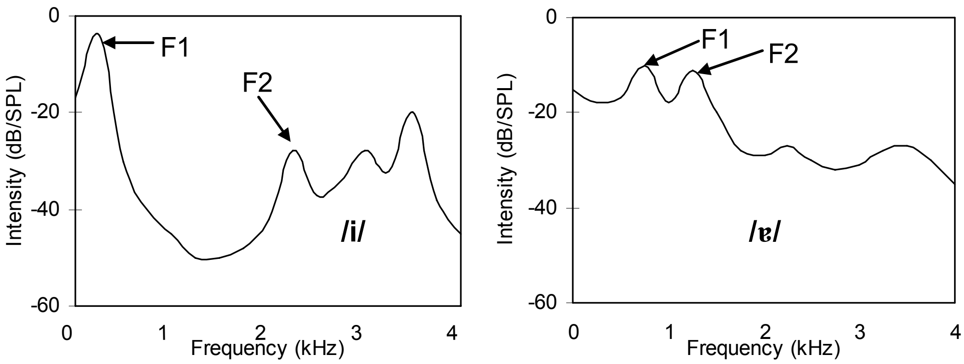


Figure 3. Spectra of /i/ and /ɐ/.
Left panel: In Australian English, /i/ has spectral peaks (or formants) at approx 300 Hz and 2200 Hz. Right panel: /ɐ/ has peaks at approx 750 Hz and 1300 Hz.
Adapted from Mannell (2008) with permission.

An early investigation of infants' perception of spectral shape showed that 1- to 4-month-old infants could discriminate the vowels /u/-/i/ and /a/-/i/ based solely on spectral shape because the vowels were presented without accompanying consonants and therefore no consonant-vowel transitions were available to aid discrimination (Trehub, 1973). More recently, Thiessen and Saffran (2004) investigated spectral tilt as a cue to word stress in a word segmentation task. Unstressed syllables tend to have a steeper negative tilt than stressed syllables, thus, when the spectral tilt of syllables is flattened, it acts as an amplitude cue to word stress. The results showed that 9-month-old infants were able to use spectral tilt alone as a stress cue, but 12-month-old infants and adults needed additional types of stress cues in order to detect stressed syllables.

6.1.1.1 Infants' Perception of Spectral Tilt in Complex Tones

A number of other studies have examined infants' perception of spectral shape using complex tones. For example, 7-month-olds have been shown to discriminate two tones with spectral shapes designed to mimic the frequency peaks found in /i/ and /a/, while ignoring variations in irrelevant acoustic cues such as duration, F0, and loudness (Trehub, Endman, & Thorpe, 1990). Infants at this age can also discriminate tonal complexes with the same F0 but different spectral shapes (Clarkson, Clifton, & Perris, 1988). In a later study, Clarkson (1996) tested 7-month-olds' ability to discriminate tones with positive or negative linear spectral tilt. This time, the tones were constructed from nine component frequencies ranging from 200 to 1800 Hz which varied in relative intensity from 3 to 27 dB. Infants were able to discriminate positive from negative spectral tilt in a simple discrimination task in which the stimuli were presented at a constant sound pressure level but found it more difficult when the stimuli varied randomly between 55 dB and 65 dB SPL. In the only other direct investigation of spectral tilt, Tsang and Trainor (2002) found that 8-month-olds could distinguish complex tones varying in spectral slope, but only within a limited range between -4 dB/octave and -10 dB/octave. In contrast to Clarkson's (1996) results, the infants were unable to distinguish tones with a positive slope (+3 dB/octave) from those with a negative slope (-3 dB/octave). Nor were they able to distinguish two tones of positive or negative tilt differing only in steepness (-16 dB/octave vs. -10 dB/octave or +4 dB/octave vs. +16 dB/octave). Tsang and Trainor suggest that infants' selective discrimination of spectral tilts between -10 and -4 dB/octave reveals a sensitivity to differences in the region most relevant to real-world speech and music.

6.1.1.2 Infants' Perception of Spectrally Tilted Speech

Until recently no research had investigated infants' perception of spectrally tilted speech in the context of amplification strategies. Although the studies by Trehub (1973) and Thiessen and Saffran (2004) both examined spectral tilt in speech, the Trehub study investigated infants' discrimination of spectral shape as a by-product of discriminating the spectra of isolated vowels, while Thiessen and Saffran's study examined spectral tilt as a stress cue. In contrast, Kitamura and colleagues have recently conducted two studies into NH infants' perception of modified spectral tilt in connected speech (Kitamura, Beach, Dillon, Ching, & Burnham, submitted; Kitamura, Dillon, Noble, Purdy, & Burnham, accepted with revisions). The first study investigated 5½- and 8-month-old infants' ability to discriminate unmodified speech from speech with a positive and negative spectral tilt (Kitamura et al., accepted with revisions). The results showed that although infants at both ages could discriminate unmodified speech from speech with a low- or high-frequency emphasis when the spectral tilt was applied at ±9 dB/octave, when the tilt was reduced to ±6 dB/octave, a developmental pattern emerged. Younger infants were *only* able to distinguish speech with low-frequency emphasis from unmodified speech, and older infants were *only* able to discriminate speech with high-frequency emphasis from unmodified speech (Kitamura et al., accepted with revisions).

The second study, which examined the attentional salience of the stimuli using a preference procedure, showed that overall, both age groups preferred high-frequency emphasis to unmodified speech, and unmodified speech to low-frequency emphasis (Kitamura et al., submitted). However, the results also indicated that younger infants were unable to differentiate between unmodified speech and speech with a high-frequency emphasis, whereas the older infants had no difficulty discriminating speech with high-frequency emphasis from unmodified speech. Thus, the authors concluded that not only did the salience of the stimuli play a role in the first discrimination study, but infants' preferences at both ages indicate a greater preference for positive over negative spectral tilt.

6.1.2 Spectral Tilt Modification

The results outlined above imply that infants prefer the sound quality afforded by positive spectral tilt, particularly as they get older. However, a more important question, and the central focus of this thesis is: How does modified spectral tilt affect the intelligibility of native-language speech contrasts which occur across the speech frequency spectrum? In line with the approach taken in earlier spectral tilt studies in our laboratory (Kitamura et al., submitted; Kitamura et al., accepted with revisions) the current study applied a moderate spectral tilt of 6 dB/octave to the speech stimuli. Thus, there were three spectral tilt conditions:

1. The natural spectral tilt of the speech contrasts remained unmodified.
2. The natural spectral tilt was altered in a positive direction by increasing the amplitude of speech information above 1000 Hz, and reducing frequencies below 1000 Hz at a rate of 6 dB/octave, resulting in speech contrasts with a high-frequency emphasis.
3. The natural spectral tilt was altered in a negative direction by increasing the amplitude of speech information below 1000 Hz, and reducing the frequencies above 1000 Hz at a rate of 6 dB/octave, thus creating speech contrasts with a low-frequency emphasis.

A 6 dB/octave tilt was selected because a slope of this magnitude is more likely to be found in hearing aid prescriptions than more extreme slopes (Dillon, personal communication, 2006). Moreover, the results of the earlier studies (Kitamura et al., submitted; Kitamura et al., accepted with revisions) suggest that a tilt of this magnitude is likely to result in a measurable impact on infants' perception of speech contrasts. Complete details of the method used to modify spectral tilt method can be found in section 7.2.2.

6.2 Speech Contrasts

The three speech contrasts were selected on the basis of their distribution in the speech spectrum. From the high-frequency region, the fricative minimal pair /f/-/s/ was selected; from the mid-frequency region, the approximant minimal pair /l/-/r/ was selected; and from the low-frequency region, the vowel minimal pair /ɐ/-/ɔ/ was selected. A second factor considered in the selection of contrasts was that they should be relatively difficult to discriminate. If the contrasts were too easy, both age groups might discriminate them under any spectral tilt condition, and thus, the use of relatively difficult contrasts (where possible) was to ensure that any differential effects of spectral tilt on discrimination performance would be observed. A full description of each of the speech contrasts follows.

6.2.1 High-frequency Fricatives

Situated at the high end of the frequency spectrum, fricatives are characterised by the high-frequency aperiodic noise that is produced by air being pushed through two closely held articulators. Typically, the concentration of energy for both /s/ and /f/ is above 4000 Hz, with higher frequency values obtained for /s/ than /f/ (Clark & Yallop, 1990). For adults, fricatives are among the most confusable contrasts in the English repertoire (Miller & Nicely, 1955) and infants, who are normally adept at discriminating speech sounds, seem to have difficulty with them too. Although there appears to be no previous studies of infants' discrimination of /f/-/s/, studies of other fricative contrasts have produced mixed results. For instance, Eilers (1977) reported that infants aged between 6 and 12 months were unable to discriminate /f/-/θ/, whereas Holmberg, Morgan, and Kuhl (1977) found that 6-month-olds could discriminate /f/-/θ/, although they were more successful with /s/-/ʃ/, requiring only half as many trials to reach a discrimination criterion. Using a CHT procedure, Nittrouer (2001) found that infants aged 6 to 14 months discriminated /s/-/ʃ/ inconsistently, although a later study reported successful discrimination of this contrast using a VH procedure (Ting, Smith, & Houston, 2006).

In this study, the fricatives were paired with the relatively low-frequency long vowel /ɐː/ to form a monosyllable with the fricative in the initial position. This particular vowel was chosen to enhance the contrastive effect of spectral tilt across the CV components of the syllable. That is, when the positive spectral tilt was applied, the high-frequency fricative information would be emphasised, while the vowel information would be suppressed. Conversely, the effect of the negative tilt would be to boost the vowel sound while de-emphasising the fricative.

6.2.2 Mid-frequency Approximants

The English approximants, sometimes known as glides or semi-vowels, are /l/, /r/, /j/ and /w/, and they are located in the mid-range of the speech spectrum. Although classed as consonants, approximants are produced in a vowel-like manner and exhibit characteristic formant patterns (Harrington & Cassidy, 1999). The most notable acoustic difference between /r/ and /l/ is in the frequency value of the third formant (F3). The approximant /r/ is characterised by a low F3 between 1300 and 1800 Hz for males (higher for females) and a corresponding steep transition into the adjacent vowel. The F3 of /l/, on the other hand, is of a higher frequency and often difficult to identify due to the attenuating effect of an antiresonance that occurs around the same frequency (Harrington & Cassidy, 1999).

Although the /l/-/r/ contrast is relatively easy for English-learning infants to discriminate, it is known to be difficult for speakers of languages in which these sounds are non-phonemic (Iverson et al., 2003; Tsushima et al., 1994). In the early months, infants for whom /l/-/r/ is native (Eimas, 1975; Karzon, 1985) and non-native (Kuhl et al., 2006; Tsushima et al., 1994) can discriminate the contrast. As infants gain more experience with their native language, their discrimination of /l/-/r/ improves such that English 10- to 12-month-olds outperform 6- to 8-month-old infants (Kuhl et al., 2006). However, Japanese 10- to 12-month olds can no longer discriminate /l/-/r/ because it is not a phonemic contrast in Japanese. Thus, infants' discrimination of /l/-/r/ follows the typical course of development for consonant perception.

In this study, /l/ and /r/ were paired with the Australian English long vowel /iː/ to create CV syllables. This vowel has a low F1 at around 300 Hz and a high F2 above 2000 Hz. The application of a negative spectral tilt to this syllable would enhance the prominence of the vowel's F1 but de-emphasise its F2, as well as the critical F3 of /l/ and /r/. Application of a positive tilt would de-emphasise the vowel's F1, and add emphasis to the higher formants, that is, the F2 of the vowel and the F3 of the approximants.

6.2.3 Low-frequency Vowels

For the third contrast, two low-frequency Australian English vowels were selected as stimuli: /ɔ/ (as in *hot*) and /ɐ/[5] (as in *hut*). These are short, lax monophthongs, and for both vowels, F1 and F2 are less than 1400 Hz. Hence, they lie adjacent to one another in the lower right portion of F1-F2 vowel space (see Appendix K). Rounded /ɔ/ is a back vowel, whereas unrounded /ɐ/ is lower, but not as far back. Unlike corner vowels which are relatively easy to discriminate, these particular vowels were chosen because their close proximity to one another on the vowel chart means that they are more difficult to discriminate (Peterson & Barney, 1952). To maintain consistency with the consonant stimuli, each vowel was presented in syllable-initial position and paired with the relatively high-frequency voiceless stop consonant /t/. This consonant was chosen to enhance the effect of spectral tilt across the VC syllable. When the negative spectral tilt was applied, high-frequency consonant

[5] Earlier Australian English transcription systems have transcribed /ɔ/ as /ɒ/ and /ɐ/ as /ʌ/. This study uses the updated Australian English transcription system proposed by Harrington, Cox and Evans (1997).

information would be suppressed, while low-frequency information, in particular the first two vowel formants, would be emphasised. Application of positive spectral tilt would have the opposite effect because it would suppress the vowel formants while boosting the intensity of the consonant.

At least two previous studies have examined infants' discrimination of similar vowel contrasts. Kuhl (1983) showed that by 6 months of age, infants have well-defined and relatively robust categories for the American English vowels, /ɑ/ as in *cot* and /ɔ/ as in *caught*, and discrimination of this vowel contrast is unaffected by variations in the speakers' gender, age, or pitch contour. A second study by Bohn (2007), using the Southern British vowels /ʌ/ and /ɒ/, was conducted as part of an investigation into asymmetric vowel discrimination, whereby infants tend to perceive two different vowels as members of the same category when the more peripheral vowel acts as the referent, but not when the less peripheral vowel is the referent category (Polka & Bohn, 2003). Bohn (2007) used a CHT procedure to show that Danish-learning infants aged between 6 and 11 months categorised the non-native vowels /ʌ/ and /ɒ/ as the same when the more peripheral vowel /ʌ/ was presented as the background stimulus, but not when the order of presentation was reversed. Although these two studies differ from the current study in terms of methods and motivation, together they indicate that the vowel contrast selected here should be discriminable by infants aged 6 months and older, when presented in its unmodified form.

6.3 Infant Ages

Infants at 6 and 9 months of age were used in this study because they are representative of two significant phases in language development. As described in the literature review of speech production and perception in previous chapters, infants progress from an acoustically driven language-general mode of speech perception to one that is linguistically driven when language-specific speech perception begins to emerge at around 9 months of age. During the first 6 months, infants rely on low-frequency speech information to process speech and recognise their native language (Mehler et al., 1988; Moon et al., 1993; Nazzi et al., 1998) and can generally perceive all speech contrasts used in human language (Eimas et al., 1971; Trehub, 1976). At around 6 months of age, infants begin to acquire native-language vowel categories (Kuhl et al., 1992; Polka & Werker, 1994) and at 9 months of age, consonants (Werker & Tees, 1984). At 9 months of age, infants rely more on phonetic than prosodic cues when listening to the native language (Jusczyk et al., 1993b; Morgan & Saffran, 1995); show a diminished preference for the exaggerated features of IDS (Hayashi et al., 2001; Panneton et al., 2006); and their speech production begins to resemble more closely the characteristics of the native language (De Boysson-Bardies & Vihman, 1991; Whalen et al., 2007). Thus, it was expected that these developmental differences would be reflected in the responses of 6-month-old and 9-month-old infants to the spectrally tilted speech contrasts.

6.4 Predictions

6.4.1 Predicted Effect of Spectral Tilt

6.4.1.1 Unmodified Spectral Tilt

Because /f/-/s/, /l/-/r/, and /ɐ/-/ɔ/ are native to the English language, and the infants in the study were from an English-language environment, it was expected that infants at both ages would have no difficulty discriminating any of the three contrasts when the natural spectral shape was unmodified.

6.4.1.2 Positive Spectral Tilt

The application of positive spectral tilt to the three speech contrasts in this study emphasised high-frequency information above 1000 Hz. Thus, it was expected that this tilt would facilitate infants' discrimination of high-frequency fricatives and mid-frequency approximants. In both of these contrasts, the acoustic features which distinguish the sounds are in this frequency range, that is, for fricatives the difference in the concentration of energy for /f/ and /s/ occurs above 4000 Hz, and for approximants, the crucial formant difference between /l/ and /r/ occurs at F3, which is above 1000 Hz. Conversely, positive spectral tilt was expected to hinder infants' discrimination of /ɐ/-/ɔ/ because the effect of the positive tilt is to de-emphasise the low-frequency range where F1 and F2 are located.

6.4.1.3 Negative Spectral Tilt

The application of negative spectral tilt to the speech contrasts in this study emphasised low-frequency information. Therefore, it was expected that negative spectral tilt would facilitate infants' discrimination of low-frequency vowels, but not mid-frequency approximants or high-frequency fricatives. Negative spectral tilt emphasises the low-frequency portion of the spectrum where the critical first two formants are located, and thus this tilt should facilitate vowel discrimination. For fricatives and approximants, on the other hand, negative tilt would be expected to have the opposite effect because negative tilt reduces emphasis on the higher frequencies. It is these higher frequencies above 1000 Hz where the critical differentiating characteristics for the approximant and fricative contrasts are located and thus, it was expected to make the differences between the fricative and approximant pairs more difficult to discern.

6.4.2 Predicted Effect of Infants' Age

Over and above the predictions based on the effect of modified spectral tilt, there were also age-related predictions. Because infants around 6 months of age still perceive speech in a language-general acoustic mode, it was predicted that they would be better able to distinguish each of the three speech contrasts in the modified spectral tilt conditions than infants aged 9 months. That is, at 6 months, discrimination performance was expected to be less susceptible to modified spectral tilt.

At 9 months of age, infants have progressed from a language-general to a language-specific mode of speech perception. Because the spectral tilt modifications interfere with the natural spectral profiles of the native speech sounds, it was anticipated that modified spectral tilt, even those that might otherwise benefit discrimination, would be problematic for 9-month-old infants. Thus, it was predicted that 9-month-olds would fail to discriminate each of the three speech contrasts in the positive and negative tilt conditions, but have no difficulty discriminating them in the unmodified spectral tilt condition.

CHAPTER 7

METHOD

This series of three experiments used a VH procedure to assess NH infants' discrimination of fricatives, approximants, and vowels under three spectral tilt conditions: (i) Normal Speech (in which the spectral tilt was unmodified); (ii) Positive Tilt (in which the speech sounds were positively tilted); and (iii) Negative Tilt (in which the speech sounds were negatively tilted).

7.1 Participants

In each of the three experiments, three groups of 32 infants were assigned to one of the three spectral tilt conditions: Normal Speech; Positive Tilt; or Negative Tilt. In each group, half the infants were 6-month-olds and half were 9-month-olds (see Table 1). The infants were recruited through an advertisement placed in *Sydney's Child* magazine (Appendix A) and all were from homes in which English was the primary language. After undergoing informed consent procedures (Appendix B) in accordance with the policies of the UWS Human Ethics Committee, parents were asked to complete a Family Information Questionnaire (Appendix C) and all reported that their infants had passed their newborn hearing screen, had no history of ear infections, and were healthy at the time of testing. Participants received a certificate (Appendix D), a small gift and a travel stipend of A$20.

In total, 362 full term infants were tested, but the data from 74 infants were discarded either because these infants failed to habituate, or were fussy, cried and did not complete the task. Failure to habituate was determined by comparing the infant's fixation duration in the final two habituation trials compared to the following two control trials of the same stimulus (full details can be found in section 7.3 below). If an infant's mean fixation duration increased by at least 100% from the habituation to control trials, they were deemed to have failed to habituate. A final sample of 288 was used in the analysis. Specific details of the number of infants who completed the task, and those who were not included are listed in Table 1.

	Condition	Σ	Age (months)		Participants not included	
		(n)	M	Range	Failed to habituate	Fussy etc.
Fricatives	Normal Speech	16	6.0	5.7 – 6.4	1	2
		16	9.0	8.5 – 9.4	2	-
	Negative Tilt	16	6.0	5.6 – 6.4	3	-
		16	8.8	8.6 – 9.2	3	-
	Positive Tilt	16	6.1	5.6 – 6.4	4	-
		16	8.9	8.7 – 9.3	6	1
		96			***19***	***3***
Approximants	Normal Speech	16	6.0	5.5 – 6.4	3	-
		16	8.9	8.6 – 9.3	1	-
	Negative Tilt	16	6.1	5.7 – 6.5	2	-
		16	8.8	8.6 – 9.3	5	-
	Positive Tilt	16	6.0	5.6 – 6.5	-	-
		16	8.9	8.6 – 9.3	5	-
		96			***16***	***0***
Vowels	Normal Speech	16	6.1	5.6 – 6.5	5	-
		16	9.1	8.7 – 9.4	6	1
	Negative Tilt	16	6.1	5.5 – 6.5	1	1
		16	8.9	8.6 – 9.3	8	1
	Positive Tilt	16	6.0	5.5 – 6.4	8	1
		16	8.9	8.5 – 9.3	4	-
		96			***32***	***4***
	Totals	***288***			***67***	***7***

Table 1. Mean age, age range, and rate of task completion for each condition.

7.2 Speech Stimuli

The speech stimuli were produced by a phonetically trained adult female speaker of Australian English. She made the recordings in a sound-attenuated room using a Rode NT2 studio microphone that was connected to a PC in an adjacent control room. An Edirol USB Audio Capture UA-25 mixer was used to interface the microphone to the PC. The speaker produced multiple clearly articulated exemplars of /fɐː/, /sɐː/, /liː/, /riː/, /ɐt/, and /ɔt/. These were digitised at a sampling rate of 22.1 kHz with 16-bit resolution and recorded directly onto the PC using speech recording and editing software, Cool Edit 2000.

Acoustic analyses were performed using Praat (Boersma & Weenink, 2005), and four well-matched tokens of each syllable were selected as stimuli. The acoustic analysis for each speech contrast differed according to the type of speech sounds in the contrast. Details of the analyses are set out below.

7.2.1 Acoustic Analyses

7.2.1.1 Fricatives

For the fricative experiment, four measures were obtained for each token of /fɐː/ and /sɐː/. Praat was used to measure (i) duration of the syllable; (ii) F0 of the vowel; (iii) centre of gravity of the fricative; and (iv) frequency of the second formant at vowel onset. The means for each measure are shown in Table 2, and the measures of the four exemplars of each syllable can be found in Appendix E. The four tokens of /fɐː/ and /sɐː/ were matched for duration and F0, but the syllables differed on the critical acoustic dimensions of centre of gravity and frequency of F2 at vowel onset. Centre of gravity measures for /f/ and /s/ reflect articulatory differences between the two fricatives (Nittrouer, Studdert-Kennedy, & McGowan, 1989). Articulation of /s/ involves a constriction at the alveolar ridge, and intense high-frequency sibilant noise is produced as the airstream strikes the teeth. Thus, the centre of gravity for /s/ is expected to be higher than for labiodental /f/ which does not generate high-intensity sibilant noise (Jongman, Wayland, & Wong, 2000). Similarly, the F2 onset frequency of /s/ is usually higher than /f/ because its place of constriction is further back in the vocal tract (Wilde, 1993). As can be seen in Table 2, the stimuli follow this pattern.

Stimulus	Duration (msec)	F0 (Hz)	Centre of gravity (kHz)	F2 at vowel onset (Hz)
/fɐː/	826 (10)	161 (5)	6.06 (.25)	1281 (36)
/sɐː/	848 (24)	160 (5)	8.15 (.01)	1325 (31)

Table 2. Mean acoustic measures for /fɐː/ and /sɐː/ averaged across four tokens.
Standard deviations are in parentheses.

7.2.1.2 Approximants

For the contrast /liː/-/riː/, four measures were obtained in order to match the tokens, and to ensure that the approximants were differentiated. These were (i) duration of the syllable; (ii) F0 at the vowel midpoint; (iii) frequency of F3 at the vowel midpoint; and (iv) frequency of F3 at the point of its onset. Table 3 contains the mean measures, and Appendix H the raw data for each of the four exemplars of each syllable. The tokens of /liː/ and /riː/ were closely matched in respect of duration, F0, and F3 at vowel midpoint, but they differed markedly on the critical F3 onset measure. Typically, the F3 of /r/ is quite low compared to that of /l/ and there is a steep transition to the following vowel (Harrington & Cassidy, 1999). This formant trajectory was observed here with the F3 of /r/ increasing from approximately 2000 Hz at onset to 3000 Hz at the midpoint of /iː/. In contrast, the F3 of /l/ was around 3000 Hz at onset and there was a relatively flat transition to the adjacent vowel.

Stimulus	Duration (msec)	F0 at vowel midpoint (Hz)	F3 at onset (Hz)	F3 at vowel midpoint (Hz)
/liː/	669 (26)	150 (0.5)	3005 (93)	3200 (23)
/riː/	645 (29)	149 (3)	2059 (55)	3164 (43)

Table 3. Mean acoustic measures averaged across four tokens of /liː/ and /riː/.
Standard deviations are in parentheses.

7.2.1.3 Vowels

The vowel stimuli, /ɐt/ and /ɔt/, were subjected to acoustic analysis using Praat to measure (i) duration; (ii) F0 at vowel midpoint; and (iii) the frequencies of F1, F2 and F3 at vowel midpoint. Mean measures of each vowel are shown in Table 4, and the raw data for each of the four exemplars of each CV syllable are available in Appendix L. As can be seen in Table 4, syllable duration and F0 were closely matched for /ɐt/ and /ɔt/. The formant frequency values were comparable to those reported for the Australian English vowels /ɐ/ and /ɔ/ (Butcher, 2006; Cox, 2006). That is, the vowels were well-differentiated in terms of the low-frequency formants, F1 and F2, whereas the frequency of F3 was similar for both vowels at approximately 2900 Hz.

Stimulus	Duration (msec)	Measures at vowel midpoint			
		F0 (Hz)	F1 (Hz)	F2 (Hz)	F3 (Hz)
/ɐt/	528 (28)	172 (2)	894 (18)	1377 (19)	2926 (32)
/ɔt/	541 (33)	175 (9)	728 (22)	1072 (13)	2889 (29)

Table 4. Mean acoustic measures across four tokens of /ɐt/ and /ɔt/.
Standard deviations are in parentheses.

7.2.2 Spectral Tilt Modification

The spectral shape of each exemplar was modified using FFT filters constructed in Adobe Audition. One filter was constructed with a negative 6 dB/octave slope, and the other with a positive 6 dB/octave slope. The filters were applied to the syllables over the full bandwidth, with the slope occurring between 250 to 4000 Hz around a fulcrum of 1000 Hz. Figure 4 shows the LTASS of the speech stimuli used in the Normal Speech, Negative Tilt and Positive Tilt conditions. The tokens with a negative 6 dB/octave spectral tilt had increased emphasis on the frequencies below 1000 Hz, and reduced emphasis on frequencies above 1000 Hz. These were used as stimuli for the Negative Tilt condition in each of the three experiments. The tokens with a positive 6 dB/octave spectral tilt had increased emphasis applied to frequencies over 1000 Hz and reduced emphasis applied to the lower frequencies.

These were used as stimuli for the Positive Tilt condition in each experiment. The original, unmodified speech tokens were used as the stimuli for the Normal Speech condition in each experiment.

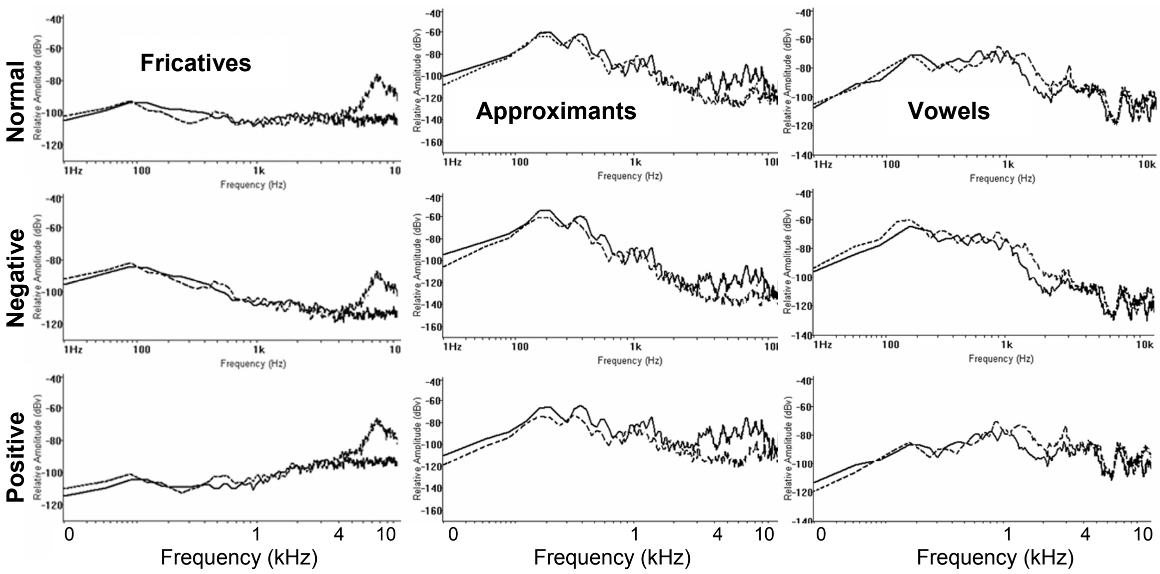


Figure 4. Long-term average speech spectra of stimuli.
Left panel: Dotted line is /s/ and solid line is /f/. Middle Panel: Dotted line is /r/ and solid line is /l/. Right panel: Dotted line is /ɐ/ and solid line is /ɔ/. In each panel, the top graph is the Normal Speech condition. The middle graph is the Negative Tilt condition, showing the effect of applying emphasis to frequencies below 1 kHz. The bottom graph is the Positive Tilt condition, showing that emphasis has been applied above 1 kHz.

Following application of positive and negative spectral tilt to the fricative, approximant and vowel contrasts, the four tokens of each syllable were spliced together to form continuous loops with a 600 ms interval between each syllable. Thus, for the fricatives, approximants and vowels, there were three stimulus types: Normal Speech, Positive Tilt, and Negative Tilt.

7.3 Visual Habituation Method

A number of experimental paradigms for testing young infants' perception have been developed since Fantz (1963) first applied the visual preference method to young infants. The method used in this thesis to examine discrimination of speech sounds under spectral tilt conditions was the VH procedure, one of two main methods used to test discrimination in infant speech perception research; the other is CHT (Werker et al., 1998). In the CHT paradigm, mother and child sit opposite the experimenter, who distracts the infant with soundless objects and facial expressions while the same background speech stimulus is played repeatedly. During the experimental phases, infants are trained to turn their head away from the experimenter and towards a reinforcer (placed approximately 45° to the infant) when the background speech stimulus changes to a new stimulus. Correct head turns are rewarded by activation of the reinforcer (usually a toy animal which dances or moves). Infants who learn to correctly turn their head to the reinforcer on presentation of the test stimulus are said to have perceived the stimulus change (e.g., Eilers et al., 1977; Werker, Polka, & Pegg, 1997).

In contrast to the training-based rationale of CHT, VH makes use of infants' natural attentional proclivities, that is, over successive presentations of the same stimulus, infants will attend for shorter periods as they habituate to the stimulus. Infants are presented with a repeating stimulus until their fixation times decrease and reach a habituation criterion. The criterion is typically a mean 50% decrement in fixation times over two or three consecutive trials compared to the mean fixation duration of the first two or three trials. Following habituation, the infant is presented with a novel test stimulus and if the infant shows a recovery response to the novel stimulus, they are deemed to have discriminated the habituation and novel stimuli (Houston, Horn, Qi, Ting, & Gao, 2007). An infant-controlled VH procedure was used here because it is more efficient than the CHT method, requiring only one researcher and taking less time to complete a test session. More importantly though, with the relatively large number of experiments planned and infants required, VH was used because it is less arduous for infants and has a much lower attrition rates than CHT, which can have drop-out rates as high as 50% as a result of infants failing the training phase and not proceeding to test trials (Werker et al., 1998).

An important procedural element in this study is the method of presentation of test trials. Rather than presenting them as a string of novel stimuli, they were presented as alternating stimuli, that is, tokens of novel and habituation stimuli alternated in the test trials. This stimulus-alternating procedure, first proposed by Best and Jones (1998), takes advantage of the fact that infants show more attention to complex than simple stimuli (Cohen, DeLoache, & Rissman, 1975; Richard, Normandeau, Brun, & Maillet, 2004). Thus, if infants detect the difference between the novel test stimulus and the habituation stimulus, their fixation times during test trials should increase because the stimulus will be perceived not only as novel, but as a complex alternating pattern. Because the procedure introduces both novelty and complexity in order to elicit infants' attention following habituation, it is a particularly robust and sensitive measure of discrimination (Best & Jones, 1998). Indeed, when Houston and colleagues (2007) compared variations of the VH procedure, this variant was found to be one of the more successful strategies.

Importantly, the VH method used here satisfies the two essential recommendations advocated by Cohen, the pioneer of VH research (Cohen, 1969; Jeffrey & Cohen, 1971). Cohen's (2004) first recommendation is that researchers use a stringent habituation criterion to ensure that infants who have not habituated are excluded from the final sample. In this study, this was accomplished firstly by applying a strict criterion for habituation. Infants were required to show a mean 50% decline in fixation duration on three consecutive trials compared to the mean fixation duration of the first three trials. Related to this was the criterion used to safeguard against spontaneous regression to the mean effects which are an indication that infants have not habituated. This was achieved by presenting two control trials *immediately following* the habituation trials. In this way, the mean of the final two habituation trials could be directly compared to the mean of the two control trials. If infants showed spontaneous regression effects, defined as an increase of at least 100% in mean fixation times in two control trials compared to the final two habituation trials, they were deemed not to have habituated and excluded from the analysis.

Cohen's second recommendation is that fixation duration in test trials should not be compared to habituation criterion trials because these trials are often artificially low (Bertenthal, Haith, & Campos, 1983). The inclusion of two control trials in the procedure satisfies this requirement. As well as being a criterion for habituation, control trial fixations were compared to test trial fixations and this difference was used to determine whether or not discrimination had occurred. Although some other VH researchers include control trials during their post-habituation test phase, few place them at the start of the test phase (e.g., Bahrick & Lickliter, 2000), and most present them scattered amongst the novel test trials (e.g., Houston et al., 2007; Polka & Werker, 1994). Placing control trials at the start of the test phase is advantageous because in this way they serve the dual purpose of (i) identifying infants who fail to habituate, and (ii) serving as the baseline comparison for test trials.

7.3.1 Materials and Apparatus

The procedure for each experiment was identical. Testing was conducted in two adjacent rooms: a sound-attenuated test room and a control room. Infants were seated on their parent's lap facing a 43 cm LCD television screen which was positioned approximately 1.5 m from the infant, and at an angle of 8° to the right of the infant's sagittal plane. The audio stimuli were presented at an average 65 dBA SPL through an Edirol micromonitor speaker placed to the immediate right of the screen. Two types of visual stimuli were presented on the screen: (i) a multi-coloured bullseye shown in conjunction with the speech stimuli during habituation, control and test trials; and (ii) a silent visual stimulus presented at the beginning of each trial to attract the infant's attention to the screen. The attention-getting stimulus was an arrangement of coloured shapes that loomed continuously from the centre of the screen. A digital video camera was positioned directly opposite the infant at eye level, and connected to (i) a DVD recorder which recorded each test session, and (ii) a television monitor in the control room, which the experimenter used to judge the infant's head and eye movements in real time. Parents were instructed not to interact with their babies, but to further minimise any possible parental influence, parents listened to repeated speech syllables (on one channel) overlaid with music (on the second channel) over AKG K270 studio headphones.

7.3.2 Procedure

Each infant was tested individually using an infant-controlled VH procedure. The habituation stimulus was presented on repeated trials until there was a mean 50% decline in fixation duration on three consecutive trials compared to the mean fixation duration of the first three trials. Thus, each infant was exposed to a minimum of six habituation trials. If the habituation criterion was not met after 30 trials had elapsed, the procedure was discontinued, and no further testing was conducted. Once the habituation criterion was met, two no-change control trials (of the habituation stimulus) were presented to ensure infants had habituated, and did not show spontaneous recovery in fixation duration. Spontaneous recovery was defined as an increase of at least 100% in mean fixation times during control trials compared to the final two habituation trials. Any infants whose fixation times met this criterion were deemed not to have habituated, and their data were excluded from the final analyses. The control trials were followed by two test trials which comprised the new test stimulus alternating with the habituation stimulus (e.g., in the fricative experiment: /sɐː/ /fɐː/ /sɐː/ /fɐː/ etc). Infants who showed recovery in fixation duration in test compared to control trials (longer mean fixation) were said to have discriminated the two stimuli. Trials began when the infant fixated the attention-getting stimulus for at least 3 seconds and ended when the infant looked away from the television screen for more than 1.2 seconds, or when a total of 30 seconds had elapsed. The experimenter recorded the infant's visual fixations to the screen by pressing the space bar on a keyboard when the infant looked at the screen, and releasing the space bar when the infant looked elsewhere. The keystrokes were recorded via purpose-written software which also controlled sequencing of the experiment.

The next three chapters present the results of the three experiments examining NH infants' discrimination of spectrally tilted fricatives (chapter 8), approximants (chapter 9), and vowels (chapter 10). These results were presented at various conferences in 2007 and 2008 and a full list is included in Appendix O. The experiments have also been submitted to *Journal of Speech, Language, and Hearing Research* and the manuscripts can be found in Appendices P, Q and R.

CHAPTER 8

RESULTS OF EXPERIMENT 1: FRICATIVES

The aim of the first experiment was to investigate the effect of modified spectral tilt on infants' ability to discriminate a high-frequency fricative contrast. Using a VH procedure, 6- and 9-month-old NH infants were tested for their discrimination of /f/-/s/ in Normal Speech, Negative Tilt, and Positive Tilt conditions.

8.1 Results

8.1.1 Preliminary Analyses

Mean fixation durations for (i) the final two habituation trials; (ii) the two no-change control trials; and (iii) the two test trials that presented the novel stimulus were calculated for each infant in each of the three conditions. Raw data are shown in Appendix F. Means and standard errors for each age group in each of the conditions are shown in Figure 5.

For each of the three conditions, a 2 (age) x (3) (trial type) ANOVA was conducted. ANOVA details can be found in Appendix G. Two planned contrasts for trial type were included in the analyses. The first contrast was used to confirm that there was no recovery in fixation duration in control trials compared to habituation trials. The second contrast tested differences in fixation duration for test trials compared to control trials, that is, whether or not the infants discriminated the two stimulus sounds or not. Where there was a significant interaction and/or a main effect for trial type, simple effects tests were conducted to examine which age group/s discriminated /f/-/s/ in each condition.

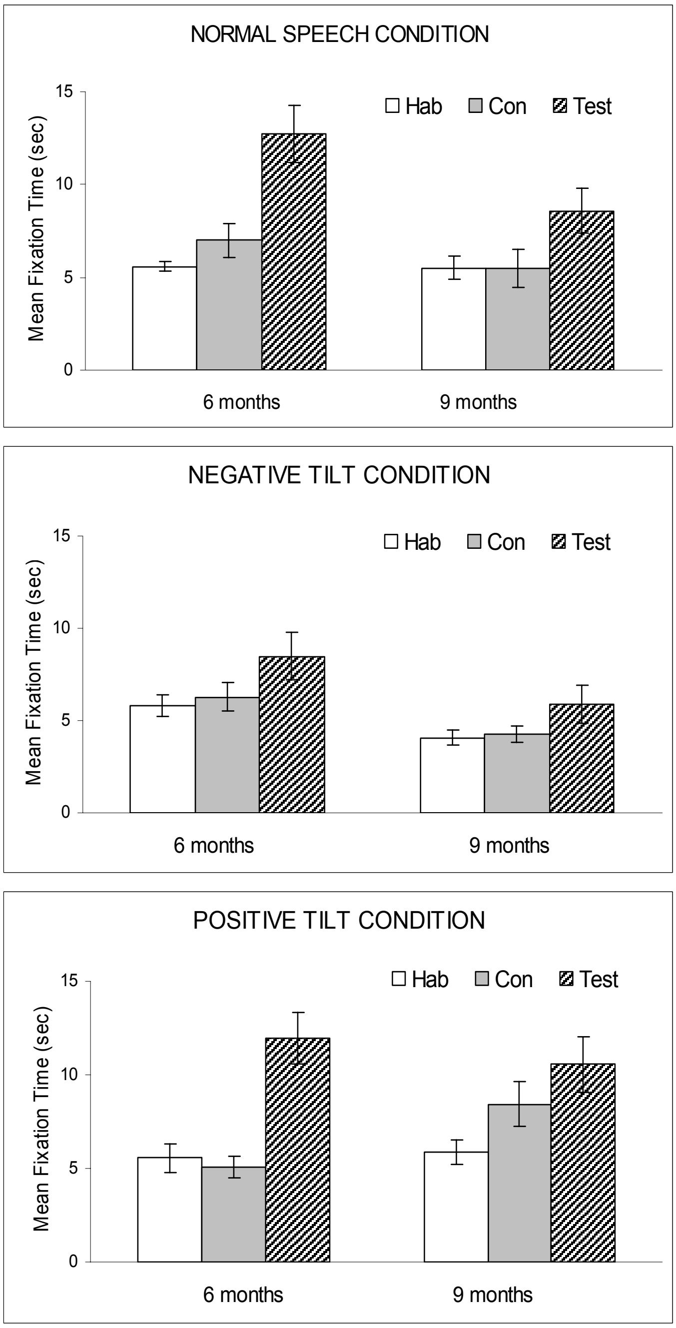


Figure 5. Fricatives: Mean fixation times for 6- and 9-month-old infants.
Top panel: Normal Speech condition, Middle panel: Negative Tilt condition, Bottom panel: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

For all three conditions, the contrast testing recovery in control trials compared to habituation trials confirmed there were no significant increase in fixation durations from habituation to control trials, all *p*s > 0.05. However, in the Positive Tilt condition, there was a significant age x trial type interaction that showed that 6-month-old infants' fixation times decreased in control trials compared to habituation trials, whereas the 9-month-old infants' fixation times increased, $F(1,30) = 8.74$, $p = 0.006$, $\eta_p^2 = 0.23$. The older infants' longer fixation times for positively tilted speech are consistent with earlier findings which showed that speech with a positive spectral tilt has a stronger attentional salience for 9-month-old than 6-month-old infants (Kitamura et al., submitted; Kitamura et al., accepted with revisions). The results for the contrast testing control versus test trials, or discrimination of /f/-/s/, in the Normal Speech, Negative Tilt, and Positive Tilt conditions are presented below.

8.1.1.1 Normal Speech Condition

The ANOVA results showed a significant main effect for trial type indicating that irrespective of age, infants increased their fixation durations in test trials ($M_{\text{test}} = 10.6$ sec) compared to control trials ($M_{\text{con}} = 6.3$ sec), $F(1,30) = 22.28$, $p < 0.001$, $\eta_p^2 = 0.43$. There was no main effect for age, or age x trial type interaction. Simple effects tests confirmed that both 6-month-old, $F(1,30) = 18.30$, $p < 0.001$, and 9-month-old infants, $F(1,30) = 5.64$, $p < 0.03$, fixated longer in the test compared to control trials. Thus, when speech was presented with a natural tilt in the Normal Speech condition, both the younger and older age groups could discriminate /f/ versus /s/.

8.1.1.2 Negative Tilt Condition

The results for the Negative Tilt condition also showed a significant main effect for trial type. Irrespective of age, infants increased their fixation durations from control trials ($M_{\text{con}} = 5.3$ sec) to test trials ($M_{\text{test}} = 7.2$ sec), $F(1,30) = 8.19$, $p < 0.01$, $\eta_p^2 = 0.21$. There was also a significant main effect for age, $F(1,30) = 5.65$, $p < 0.03$, $\eta_p^2 = 0.16$, indicating that, as is typical when testing infants of these ages, 6-month-olds' fixation durations ($M_{6mo} = 6.9$ sec) were longer than those of 9-month-olds ($M_{9mo} = 4.7$ sec). There was no age x trial type interaction. Simple effects tests revealed that the 6-month-old infants fixated significantly longer during test trials compared to control trials, $F(1,30) = 6.02$, $p < 0.02$, but the result for 9-month-old infants was not significant, $p > 0.11$. The results indicate that although the younger infants were able to discriminate /f/-/s/ successfully in the Negative Tilt condition, the older group found discrimination in this condition more difficult.

8.1.1.3 Positive Tilt Condition

In the Positive Tilt condition, there was a significant main effect for trial type revealing longer fixation durations in test trials (M_{test} = 11.3 sec) compared to control trials (M_{con} = 6.7 sec), $F(1,30) = 19.12$, $p < 0.001$, $\eta_p^2 = 0.39$. More importantly, there was a significant age x trial type interaction, $F(1,30) = 5.39$, $p < 0.03$, $\eta_p^2 = 0.15$, indicating that 6-month-old infants showed a larger increase in fixation times from control to test trials than 9-month-old infants. The superior performance of the younger group was confirmed by simple effects tests which were significant for 6-month-old infants, $F(1,30) = 40.12$, $p < 0.001$, but not 9-month-old infants, $p > 0.2$. The results from the Positive Tilt condition clearly show that the younger infants, but not the older infants, were able to discriminate the fricative contrast when high-frequency emphasis was applied.

8.1.2 Discrimination Indices

The above analyses show that 6-month-old infants can discriminate /f/-/s/ regardless of whether the contrast is presented as normal unmodified speech or with a positive or negative spectral tilt. Nine-month-old infants, on the other hand, can only discriminate /f/-/s/ when it is presented as normal unmodified speech. To probe each age group's relative ability to discriminate /f/-/s/ across conditions, a discrimination index (DI) was determined by calculating the amount of time infants spent fixating in test trials as a proportion of the time spent fixating during both control and test trials (DI = test/test+control). Because the DI factors out individual differences in fixation durations, it allows for comparisons between infants in the three conditions. A DI greater than 0.50 indicates that an infant looked longer during test than control trials and the DI approaches 1 as the relative difference between test and control fixations increases. Thus, the DI is a type of novelty preference score, such that a group of infants with a mean DI significantly above 0.50 indicates that the group discriminated the test and control stimuli (Arterberry & Bornstein, 2002). A DI was calculated for each infant in each age group, and the mean DIs for each age group and condition are shown in Figure 6. DIs for individual infants can be found in Appendix F.

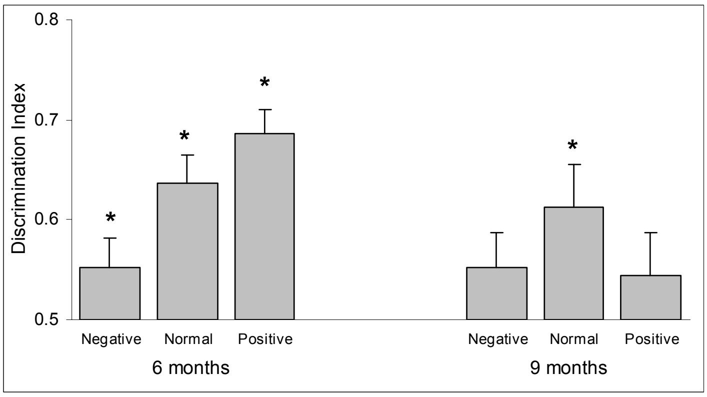


Figure 6. Fricatives: Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
There is a linear improvement across conditions for the 6-month-old infants, but not for the 9-month-old infants. Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

In the analysis, each mean DI was compared to chance performance using one-tailed t-tests. The results showed that the 6-month-olds' DIs were above chance in the three conditions: Normal Speech, $t(15) = 4.76$, $p < 0.001$; Negative Tilt, $t(15) = 1.76$, $p < 0.05$; and Positive Tilt, $t(15) = 7.89$, $p < 0.001$. For 9-month-olds, the DI exceeded chance in the Normal Speech condition, $t(15) = 2.67$, $p < 0.02$, but not the Negative or Positive Tilt conditions, *p*s > 0.08. These results are consistent with the analyses of fixation durations presented earlier. That is, 6-month-olds are capable of discriminating /f/-/s/ regardless of whether spectral tilt is modified or not, whereas 9-month-olds discriminated /f/-/s/ only in the unmodified condition.

In a second analysis, the DIs were entered into a 2 (age) x 3 (condition) ANOVA (see Appendix G for details). Planned contrasts tested for linear and quadratic trends across the three equally spaced tilt conditions[6]: Negative Tilt (tilt factor: -6); Normal Speech (tilt factor: 0); and Positive Tilt (tilt factor: +6). These contrasts were included to ascertain the pattern of discrimination performance across

[6] See Howell (2007) for more information about linear and quadratic polynomial contrasts in ANOVA.

the three conditions, and specifically, whether performance improved as the tilt factor increased.

The results revealed a significant linear x age interaction, $F(1,90) = 4.09$, $p < 0.05$, $\eta_p^2 = 0.12$. The quadratic trend for condition was not significant and there was no significant main effect for age. As shown in Figure 6, there was an upward linear trend across the three conditions for 6-month-old infants, $DI_{Neg} < DI_{NS} < DI_{Pos.}$ This means that the younger infants discriminated fricatives best in the Positive Tilt condition, and better in the Normal Speech than the Negative Speech condition. However, for the 9-month-olds, discrimination performance peaked in the Normal Speech condition, $DI_{NS} > DI_{Pos} \approx DI_{Neg}$. Separate ANOVAs for each age group confirmed the significant linear trend for 6-month-old infants, $F(1,45) = 12.04$, $p < 0.001$, but for 9-month-olds, neither the linear, $p > 0.9$, nor the quadratic trend, $p > 0.1$, was significant.

8.2 Discussion

Experiment 1 examined how modifying the spectral tilt of the high-frequency fricative contrast /f/-/s/ influenced discrimination by 6- and 9-month-old NH infants. The results revealed that 6-month-old infants could discriminate the fricatives, irrespective of whether they remained unmodified or had high- or low-frequency emphasis. On the other hand, older infants could discriminate the contrast only when it was unmodified, with its natural spectral slope intact. When DIs are used as a measure of discrimination performance, it is clear that 6-month-old infants' performance improves as the direction of tilt changes from negative to positive, but that of 9-month-old infants does not. Thus, although it might have been expected that high-frequency emphasis would facilitate discrimination of high-frequency fricatives, this proved to be the case only for 6-month-old infants; 9-month-old infants performed best in the Normal Speech condition. How do these results bear on the hypotheses? First, it was proposed that positive spectral tilt would facilitate the discrimination of fricatives because of the high-frequency emphasis it provides. Although this expectation was met for 6-month-old infants, it was not the case for the older infants, who seemed to find the Positive Tilt just as difficult as the Negative Tilt condition. Second, it was predicted that 6-month-old infants would be able to discriminate /f/-/s/ in all three conditions because of their language-general mode of speech perception, and that 9-month-old infants would discriminate the contrast only in the Normal Speech condition because of their increasingly language-specific speech perception strategies. The results confirm this prediction, with 6-month-old infants able to discriminate /f/-/s/ in all three conditions and 9-month-old infants in the Normal Speech condition only.

It is unknown whether the developmental effect found for fricative discrimination is indicative of a generalised effect that applies to a range of speech contrasts, or whether it is peculiar to those consonants whose energy is concentrated in the high-frequency region. This question was pursued in Experiments 2 and 3. Experiment 2 investigated the effect of modified spectral tilt on the discrimination of mid-frequency approximants and the results are presented in the next chapter.

CHAPTER 9

RESULTS OF EXPERIMENT 2: APPROXIMANTS

The goal of the current study was to extend the findings of Experiment 1 to a new class of sounds, characterised by a concentration of energy in the lower frequencies: approximants. NH infants aged 6 and 9 months were tested for their discrimination of /l/ and /r/ using a VH procedure.

9.1 Results

9.1.1 Preliminary Analyses

The mean fixation durations in (i) the final two habituation trials; (ii) the two no-change control trials; and (iii) the two novel test trials were calculated for each infant in each of the three conditions. Raw data are shown in Appendix I. Means and standard errors for each age group in each of the three conditions are shown in Figure 7.

For each condition, a 2 (age) x (3) (trial type) ANOVA was conducted (see Appendix J for details) with two planned contrasts. The first contrast was to verify that there was no recovery in fixation duration in the control trials compared to habituation trials. The second contrast tested whether or not the infants discriminated the two stimulus sounds, that is, whether or not fixation durations were longer in test trials compared to control trials. Where there were significant interactions and main effects for trial type, simple effects tests were performed to ascertain which of the two age groups discriminated the approximant contrast in each condition.

In all three conditions, the contrast testing fixation recovery in control trials compared to habituation trials confirmed there were no differences in fixation durations for the two trial types, all *p*s > 0.2. That is, neither age group showed a spontaneous regression to the mean effect in any of the three conditions. The results for the contrast testing whether there was a difference between control and test trials in each of the three conditions are detailed below.

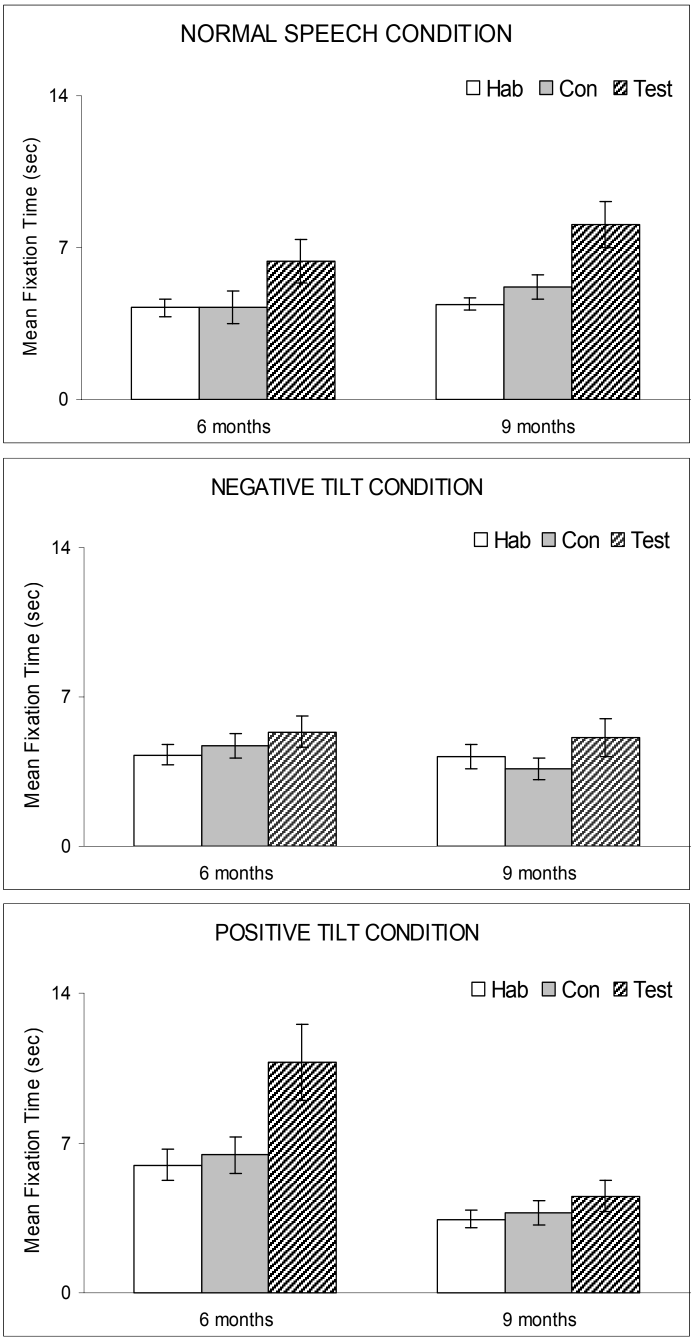


Figure 7. Approximants: Mean fixation times for 6- and 9-month-old infants.
Top: Normal Speech condition, Middle: Negative Tilt condition, Bottom: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

9.1.1.1 Normal Speech Condition

The results of the ANOVA showed a significant main effect for trial type indicating that fixation duration increased in test trials (M_{test} = 7.2 sec) compared to control trials (M_{con} = 4.7 sec), $F(1,30) = 9.42$, $p < 0.01$, $\eta_p^2 = 0.24$. The main effect for age and age x trial type interaction were not significant. Simple effects tests confirmed that both 6-month-old, $F(1,30) = 4.99$, $p < 0.04$, and 9-month-old infants, $F(1,30) = 4.71$, $p < 0.04$, had longer fixation durations in test compared to control trials. Thus, both age groups were able to discriminate /l/-/r/ in the Normal Speech condition.

9.1.1.2 Negative Tilt Condition

In the Negative Tilt condition, the ANOVA showed no significant main effect for trial type, indicating that there was no difference in fixation duration between test trials (M_{test} = 5.2 sec) and control trials (M_{con} = 4.2 sec), $p > 0.07$. The main effect for age and the age x tilt type interaction were also not significant. Thus, both age groups failed to discriminate /l/-/r/ when low-frequency information was emphasised in the Negative Tilt condition.

9.1.1.3 Positive Tilt Condition

In the Positive Tilt condition, the ANOVA results revealed a significant main effect for trial type, $F(1,30) = 9.81$, $p < 0.01$, $\eta_p^2 = 0.25$, and age, $F(1,30) = 14.94$, $p < 0.001$, $\eta_p^2 = 0.33$, and a significant age x trial type interaction, $F(1,30) = 4.66$, $p < 0.04$, $\eta_p^2 = 0.13$. These results indicate that irrespective of trial type, 6-month-olds (M_{6mo} = 7.7 sec) fixated longer than 9-month-olds (M_{9mo} = 3.9 sec). The main effect for trial type reveals that infants showed a recovery in fixation duration during test trials (M_{test} = 7.6 sec) compared to control trials (M_{con} = 5.1 sec). More importantly though, the significant trial type x age interaction shows that 6-month-old infants had a larger increase in fixation durations than 9-month-old infants. When analysed for simple effects, the results show that 6-month-old infants, $F(1,30) = 7.92$, $p < 0.01$, but not 9-month-old infants, $p > 0.16$, could discriminate /l/-/r/ in the Positive Tilt condition. Thus, younger infants successfully discriminated /l/-/r/ when high-frequency emphasis was added, whereas their older counterparts were unable to do so.

9.1.2 Discrimination Indices

To investigate each group's relative discrimination performance across the three conditions, additional analyses were conducted using DIs as described in the earlier fricative experiment (see section 8.1.2). Recall that a DI is calculated by expressing fixation duration in test trials as a proportion of fixation duration in both control and test trials. A DI was calculated for each infant (see Appendix I) and the mean DIs for each of the two age groups and the three conditions are shown in Figure 8.

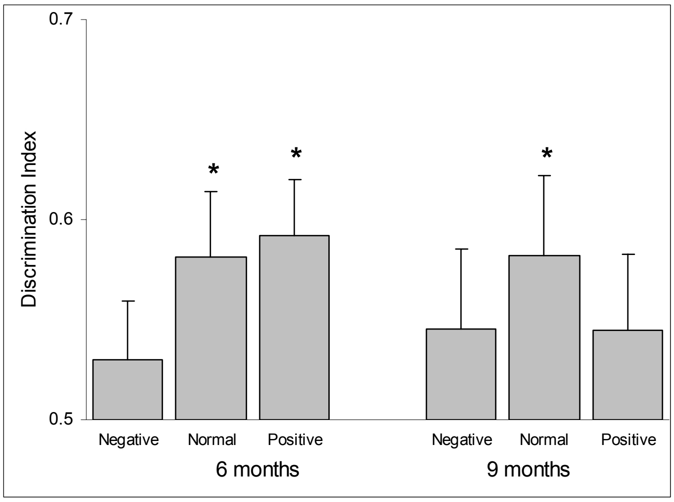


Figure 8. Approximants: Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

In the analysis, each group's mean DI was compared to chance (0.50) using one-tailed t-tests. The t-tests revealed that the 6-month-olds' DIs were above chance in the Normal Speech, $t(15) = 2.51$, $p < 0.02$, and Positive Tilt conditions, $t(15) = 3.31$, $p < 0.003$, but not the Negative Tilt condition, $p > 0.17$. For 9-month-olds, the DI exceeded chance in the Normal Speech condition, $t(15) = 2.04$, $p < 0.03$, but not the Negative or Positive Tilt conditions, *p*s > 0.12. These results support the ANOVAs of fixation durations. Both age groups discriminated /l/-/r/ in the Normal Speech condition; neither group discriminated the approximants in the Negative Tilt condition; and only the 6-month-olds discriminated the contrast in the Positive Tilt condition.

To compare discrimination performance across conditions, the DIs of infants in both age groups were analysed in a univariate 2 (age) x 3 (condition) ANOVA. Details of the ANOVA can be found in Appendix J. Planned contrasts were included to test for linear and quadratic trends across the three equally spaced conditions: Negative Tilt (tilt factor: -6); Normal Speech (tilt factor: 0); and Positive Tilt (tilt factor: +6). The purpose of these contrasts was to determine whether there was a linear improvement in discrimination performance as tilt factor increased, as was shown for the 6-month-old group in Experiment 1 (fricatives) or whether the DIs for each condition followed a quadratic trend. Although no significant results were found here in Experiment 2, it is worth noting that the mean DIs for approximants, shown in Figure 8, follow the same trends found for fricatives in Experiment 1. That is, discrimination of approximants for 6-month-old infants improved from Negative to Positive Tilt, whereas for 9-month-old infants, discrimination in the Normal Speech condition was superior to that of the two spectral tilt conditions.

9.2 Discussion

The results show that both 6- and 9-month-old infants could discriminate the /l/-/r/ approximant contrast when it was presented in the Normal Speech condition. In the Positive Tilt condition, 6-month-old infants discriminated /l/-/r/, whereas 9-month-old infants failed to discriminate the contrast in this condition. Interestingly, neither group could discriminate the contrast in the Negative Tilt condition. Thus, it seems that overall, 6-month-old NH infants are better than 9-month-olds at discriminating speech with modified spectral tilt. An examination of DIs suggests that the same general trends found for fricatives occurred for approximants. That is, 6-month-old infants' discrimination performance improves as the degree of tilt increases, while 9-month-old infants perform best in the Normal Speech condition. However, these trends were not significant in the case of approximants.

The failure of 9-month-old infants to discriminate /l/-/r/ with modified spectral tilt is in accord with the results reported for the fricative contrast. Thus, for both high- and mid-frequency consonants, older infants demonstrate an inability to discriminate spectrally tilted phonemic contrasts. For 6-month-old infants, the results of the fricative study were only partially supported. In the approximant experiment, younger infants showed more flexible discrimination abilities than older infants, given that they could discriminate /l/-/r/ in both the Positive Tilt and Normal Speech conditions. However, with approximants, the 6-month-olds found the Negative Tilt condition problematic. As noted earlier, the application of negative spectral tilt increases the amplitude of low-frequency energy and de-emphasises the F3 difference between the two sounds. This amplitude imbalance may have resulted in not only a reduction in the prominence of the critical formant information, but perhaps also a masking effect, whereby the louder low-frequency information suppressed the now quieter, yet critical high-frequency information, thus rendering the contrast difficult for both age groups in the Negative Tilt condition.

In summary, this study confirms that 6- and 9-month-old NH infants respond to modified spectral tilts in distinctly different ways. In order to complete the picture of how spectral tilt affects discrimination of sounds across the full speech spectrum, a third experiment was conducted investigating the effect of spectral tilt on NH infants' discrimination of low-frequency vowels.

CHAPTER 10

RESULTS OF EXPERIMENT 3: VOWELS

The goal of the third experiment in the series was to investigate how modified spectral tilt influences 6- and 9-month-old NH infants' ability to discriminate a native-language low-frequency vowel contrast /ɐ/-/ɔ/.

10.1 Results

10.1.1 Preliminary Analyses

As for the previous two experiments, mean fixation durations were calculated for (i) the final two habituation trials; (ii) the two no-change control trials; and (iii) the two novel test trials for each infant in each of the three conditions. Raw data are shown in Appendix M. Figure 9 displays the mean fixation durations for habituation, control, and test trials for 6- and 9-month-old infants in each of the three conditions.

For each condition, a 2 (age) x (3) (trial type) ANOVA was conducted (see Appendix N for details) with two planned contrasts. The first contrast tested the difference in fixation durations between habituation and control trials to confirm infants did not show a fixation recovery in control trials. The second contrast tested the difference in fixation durations between control and test trials, that is, whether or not infants discriminated /ɐ/ and /ɔ/. Significant interactions and main effects for trial type were followed by simple effects tests to determine whether 6- or 9-month-olds were able to discriminate the vowels in each condition.

In all three conditions, the contrast testing recovery in control trials showed there were no significant differences in fixation durations between habituation and control trials, all ps > 0.07. The results for the contrast testing the difference between no-change control trials and test trials are reported below. Recovery in test trials was used to determine whether infants could discriminate /ɐ/-/ɔ/ in each of the three conditions.

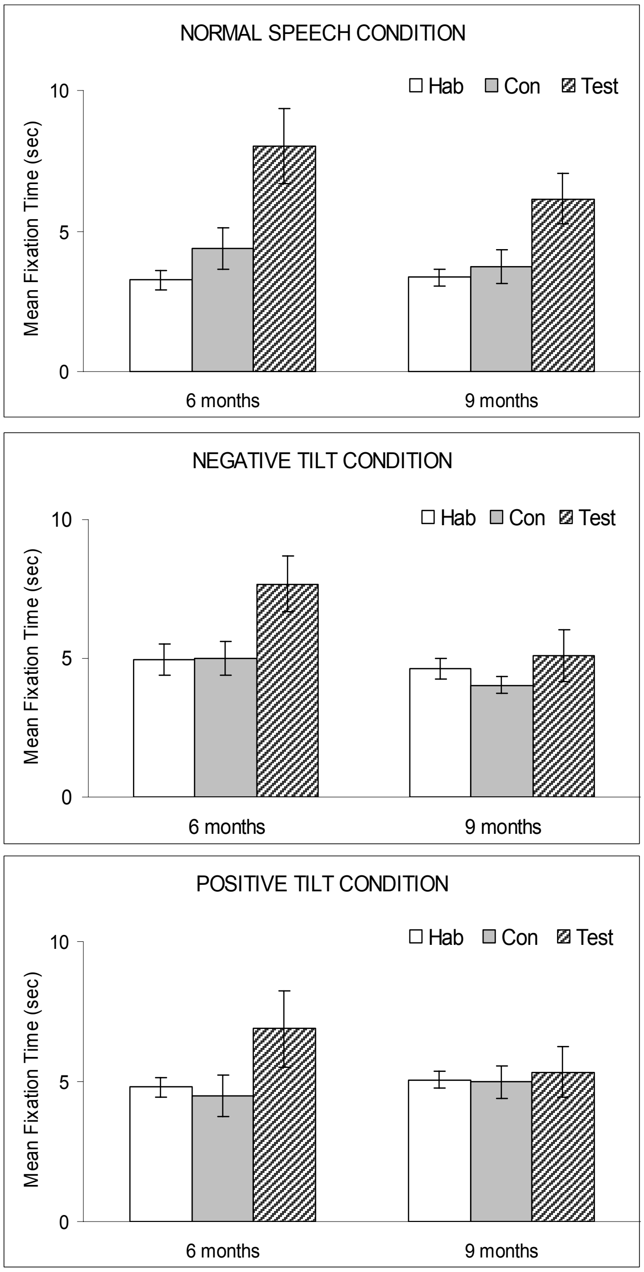


Figure 9. Vowels: Mean fixation times for 6- and 9-month-old infants.
Top panel: Normal Speech condition, Middle panel: Negative Tilt condition, Bottom panel: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

10.1.1.1 Normal Speech Condition

The ANOVA showed a significant main effect for trial type, indicating an increase in fixation durations for test trials (M_{test} = 7.1 sec) compared to control trials (M_{con} = 4.1 sec), $F(1,30) = 13.81$, $p < 0.001$, $\eta_p^2 = 0.32$. There was no main effect for age or age x trial type interaction. Simple effects tests confirmed that infants at both 6 months, $F(1,30) = 5.76$, $p < 0.02$, and 9 months, $F(1,30) = 16.43$, $p < 0.001$, had longer fixation durations in test compared to control trials. Thus, both younger and older infants discriminated the vowel contrast /ɐ/-/ɔ/ in the Normal Speech condition.

10.1.1.2 Negative Tilt Condition

The results for this condition also showed a significant main effect for trial type. Fixation duration was greater in test trials (M_{test} = 6.4 sec) compared to control trials (M_{con} = 4.5 sec), $F(1,30) = 5.97$, $p < 0.03$, $\eta_p^2 = 0.17$. The main effect for age was significant, $F(1,30) = 4.20$, $p < 0.05$, $\eta_p^2 = 0.12$, indicating that overall, 6-month-olds (M_{6mo} = 5.9 sec) looked longer than 9-month-olds (M_{9mo} = 4.6 sec). There was no age x trial type interaction. Simple effects tests showed that 6-month-old infants successfully discriminated the vowels in the Negative Tilt condition, $F(1,30) = 4.97$, $p < 0.04$, but the result for 9-month-old infants was not significant, $p > 0.2$. That is, younger, but not older, infants were able to discriminate /ɐ/-/ɔ/ when low-frequency emphasis was applied to the vowel contrast in the Negative Tilt condition.

10.1.1.3 Positive Tilt Condition

In the Positive Tilt condition there was no significant main effect for trial type, indicating that irrespective of age, there was no increase in fixation duration during test trials (M_{test} = 6.1 sec) compared to control trials (M_{con} = 4.7 sec), $p > 0.08$. The main effect for age and the age x trial type interaction were also not significant. The difficulty infants experienced in this condition may have been caused by the positive tilt boosting the amplitude of the high-frequency region of the spectrum while decreasing the amplitude of the low-frequency region, thereby obscuring the critical first two formants which effectively differentiate these two vowels.

10.1.2 Discrimination Indices

To gain a clearer picture of each age group's relative discrimination performance across the three tilt conditions, further analyses were conducted using DIs as the dependent variable (previously described in section 8.1.2). For each infant in each age group, a DI was calculated (see Appendix M) and the means for each age group and condition are shown in Figure 10.

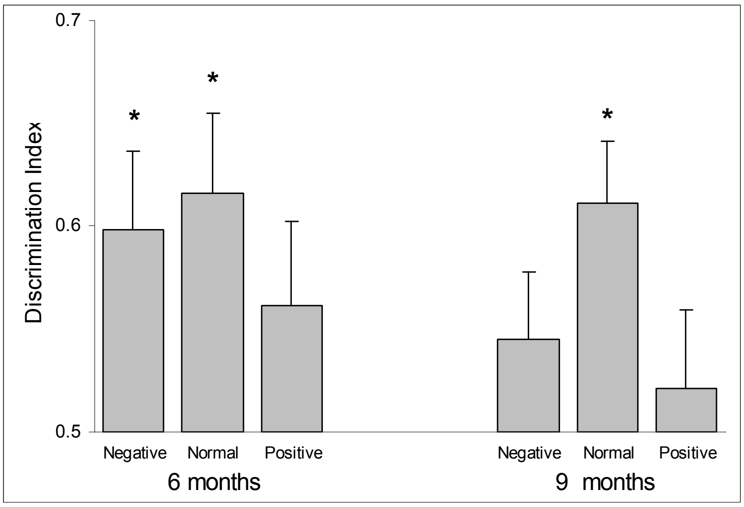


Figure 10. Vowels: Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
Both age groups show a quadratic trend. Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

One-tailed t-tests were conducted on the mean DIs to examine whether the DIs were above chance performance (0.50). The results revealed that DIs were above chance in the Normal Speech condition for infants aged 6 months, $t(15) = 2.94$, $p < 0.006$, and 9 months, $t(15) = 3.72$, $p < 0.002$. The results also revealed that 6-month-olds' DI in the Negative Tilt condition was significantly above chance, $t(15) = 2.61$, $p < 0.01$. Thus, the DI analysis supports the analysis of fixation durations in showing that 6-month-olds discriminated /ɐ/-/ɔ/ in the Normal Speech and Negative Tilt conditions, whereas 9-month-olds discriminated /ɐ/-/ɔ/ only in the unmodified condition.

Next, the DIs of all infants were analysed in a 2 (age) x 3 (condition) ANOVA (see Appendix N for details) and planned contrasts tested for linear and quadratic trends across the three conditions. Recall that the three conditions are equally spaced in terms of spectral tilt: Negative Tilt (tilt factor: -6); Normal Speech (tilt factor: 0); and Positive Tilt (tilt factor: +6). There was no significant main effect for age, linear trend for condition, or any interactions. However, averaged across age groups, the quadratic trend was significant, $F(1,90) = 3.91$, $p < 0.05$. This result suggests that for both 6- and 9-month-old infants, discrimination was strongest in the Normal Speech condition as shown in Figure 10. This similarity in the performance of 6- and 9-month-old infants suggests that there is an emerging tendency for 6-month-old infants to perceive native vowels in a more constrained manner, just as older infants do with vowels, approximants, and fricatives. That is, because attunement to native vowels occurs earlier than for consonants, 6-month-olds are starting to find modified spectral tilt an unhelpful distraction and will soon reach the stage where they discriminate only those native vowels that exhibit a normal spectral profile.

10.2 Discussion

In summary, the results show that both 6- and 9-month-old infants could discriminate /ɐ/-/ɔ/ when they were presented in the Normal Speech condition. In addition, 6-month-old infants could discriminate /ɐ/-/ɔ/ in the Negative Tilt condition, but neither group could discriminate the low-frequency vowel contrast in the Positive Tilt condition. Despite negative spectral tilt providing what should be helpful low-frequency emphasis, older infants failed to discriminate the vowel contrast in this condition. The DI analyses confirmed that for 9-month-old infants, discrimination was best in the Normal Speech condition. Moreover, the DI analyses revealed that 6-month-old infants *also* performed best in the Normal Speech condition. This seems to reflect the fact that infants attune to native-language vowels before consonants, and hence 6-month-old infants are starting to find spectral tilt an unwelcome modification to vowels, just as older infants do with both consonants and vowels.

The results of the three experiments presented in this thesis have consistently demonstrated that 6- and 9-month-old infants discriminate speech contrasts with modified spectral tilt in distinctly different ways. In each of the three experiments, 9-month-olds discriminated the speech contrasts *only* in the Normal Speech condition. Both positive and negative spectral tilts adversely affected older infants' ability to discriminate speech contrasts, even when the tilt emphasised acoustically useful information, that is, high-frequency information for consonants, and low-frequency information for vowels. In contrast to their older counterparts, younger infants repeatedly showed that they can discriminate contrasts with altered spectral tilts. In the first two experiments testing fricatives and approximants, the discrimination performance of younger infants improved when positive spectral tilt was applied, likely because positive tilt emphasised the crucial high-frequency cues which differentiated these stimuli. In the current vowel experiment, the stimuli differed in the low-frequency portion of the speech spectrum, and when this region was emphasised in the Negative Tilt condition, the younger infants' discrimination performance was similar to their performance in the Normal Speech condition.

The developmental trend evident in these results has important implications not only for our understanding of speech perception in NH infants, but also for HI infants. These implications will be discussed in the final chapter.

CHAPTER 11

GENERAL DISCUSSION

11.1 Summary of Findings

The three experiments presented in this thesis show that modified spectral tilt affects 6- and 9-month-old NH infants' discrimination of speech sounds in demonstrably different ways. In Experiment 1, 6-month-old infants discriminated /f/-/s/ in all three tilt conditions, and discrimination performance improved as the emphasis on high-frequency information increased, that is, from Negative to Positive Tilt. Nine-month-olds discriminated /f/-/s/ in the Normal Speech condition only and thus their best performance was in the Normal Speech condition. In Experiment 2, 6-month-old infants discriminated /l/-/r/ in the Normal Speech and Positive Tilt conditions, whereas 9-month-olds discriminated the approximants in the Normal Speech condition only. In Experiment 3, 6-month-old infants discriminated /ɐ/-/ɔ/ in the Normal Speech and Negative Tilt conditions, whereas 9-month-olds discriminated the vowel contrast in the Normal Speech condition only. Both 6- and 9-month-olds discriminated the vowels best in the Normal Speech condition.

It had been predicted that 9-month-old infants would demonstrate sensitivity to spectral tilt modifications and discriminate the contrasts only in the Normal Speech condition. This expectation was met in each of the three experiments. That is, 9-month-olds discriminated the fricatives, approximants and vowels *only* in the Normal Speech condition. The failure of 9-month-olds to discriminate speech contrasts with modified spectral tilt was observed regardless of the tilt direction, and irrespective of whether the speech contrasts contained predominantly high- mid- or low-frequency information. Even when the modified spectral tilt provided what should have been acoustically useful information, 9-month-olds failed to show a discrimination response. Thus, the results indicate that 9-month-olds are particularly sensitive to any deviations from the normal speech spectrum, and their speech discrimination suffers as a consequence.

A different pattern of perceptual behaviour was expected for 6-month-olds. It was predicted that the younger infants' speech perception would be less susceptible to spectral tilt modifications, and that they would be able to discriminate contrasts with modified spectral tilt. The results confirmed this expectation with 6-month-olds demonstrating a superior ability to accommodate spectral tilt modifications. Across the three experiments, they discriminated each of the three contrasts in at least one of the altered tilt conditions. That is, in addition to discriminating all contrasts in the Normal Speech condition, 6-month-olds discriminated high-frequency fricatives in the Positive and Negative Tilt conditions; mid-frequency approximants in the Positive Tilt condition; and low-frequency vowels in the Negative Tilt condition. Furthermore, in accordance with the predictions regarding the effect of spectral tilt, the emphasis of relevant frequency information facilitated 6-month-olds' discrimination performance. That is, high-frequency emphasis benefited 6-month-olds' discrimination of fricatives and approximants, whereas low- but not high-frequency emphasis facilitated vowel discrimination. Thus, compared to 9-month-olds, 6-month-olds' speech perception was relatively unimpeded by spectral tilt modifications and younger infants were able to make use of the enhanced acoustic information afforded by the spectral tilt manipulations.

11.2 Development of Infant Speech Perception

At first glance, the finding that younger infants discriminate modified speech sounds more successfully than older infants seems counterintuitive. After all, there is considerable evidence that 6-month-old infants' general auditory perception abilities, such as intensity perception (Trehub et al., 1988) and frequency discrimination (Aslin, 1989; Olsho, 1984) are not as well developed as those of 9-month-old infants. If the speech discrimination tasks used in these experiments were simply a matter of detecting acoustic differences, then one would expect the 9-month-olds to outperform the 6-month-olds because of the older infants' superior auditory skills. The poorer performance by 9-month-olds suggests that for them, these tasks are not merely a matter of detecting acoustic differences but rather, they are linguistic tasks, which invoke 9-month-olds' newly emerging language-specific mode of speech perception.

The infant's progression from an early language-general phase of speech perception to one that is language-specific at around 9 months of age is well-documented. During the first six months of life, infants perceive speech at an acoustic, rather than a phonetic or phonological level (Aslin & Pisoni, 1980). This underlies their ability to discriminate the range of phonetic segments found in human language (Eimas et al., 1971; Trehub, 1976). In this early phase, infants easily discriminate native and non-native segments, but by 6 months of age, experience-related effects emerge for vowels, showing that phonetic categories are becoming organised around native-language prototypes (Kuhl et al., 1992; Polka & Werker, 1994). During the second phase of language development, more 'phonetic learning' takes place; the infant's perceptual system undergoes reorganisation and infants' phonetic perception becomes aligned with the inventory of native-language speech sounds (Polka & Werker, 1994; Werker & Tees, 1984). For consonants, improvement in the perception of native segments first becomes evident at around 10 to 12 months of age, (Kuhl et al., 2008) and there is a concomitant decline in the perception of most non-native sounds (Werker & Tees, 1984).

In parallel with the infant's increasingly language-specific segmental perception, there is also a growing ability to recognise finer details of the suprasegmental aspects of their native language. In the early months, infants rely on suprasegmental information to recognise the native language (Mehler et al., 1988; Moon et al., 1993), but as experience with the ambient language accumulates, infants' perceptual capabilities become increasingly sensitive to native-language phrasal and lexical stress patterns (Jusczyk et al., 1993a; Jusczyk et al., 1992). As infants approach 9 months of age, they start to pay less attention to the suprasegmental aspects of speech (Friederici & Wessels, 1993) and their segmental perception has become sufficiently developed such that they can recognise their native language via its phonetic and phonotactic features (Jusczyk et al., 1993b). Clearly, there is a significant developmental shift in speech perception that occurs between 6 and 9 months of age and this is reflected in the differential effect of modified spectral tilt on 6- and 9-month-old infants' speech discrimination. Older infants, who are in the midst of an intense period of perceptual reorganisation for native-language inventories of vowels and consonants, discriminate only those contrasts presented as natural, unmodified speech. Younger infants, on the other hand, who are not attuned to native speech to the same extent as older infants, are able to accommodate modified spectral profiles, and their acoustic mode of perception means that they benefit when acoustic differences between sounds are emphasised.

Nine months of age seems to be a critical point in the infant's language development trajectory. Not only is it a time of intensive perceptual reorganisation, it is also the age at which infants start showing an aversion to the exaggerated prosody of IDS (Hayashi et al., 2001; Panneton et al., 2006); canonical babbling becomes established (Oller, 1980, 2000); and infant vocalisations start to more closely resemble the features of the native language (De Boysson-Bardies & Vihman, 1991; Whalen et al., 2007). Thus, 9 months seems to mark the time when infants' perception *and* production of speech are simultaneously converging towards the native language. The onset of native-like canonical babbling may provide infants with important new proprioceptive cues that help them establish both perceptual and productive native categories at this age. In future studies, it would be useful to examine the perception of modified spectral tilt in infants older than 9 months of age to determine whether modified spectral tilt continues to show an adverse effect on speech discrimination. It might be that once this particularly intense period of perceptual reorganisation and linguistic development has passed, infants will be better able to accommodate modifications to native-language spectral profiles.

11.3 Acquisition of Native-language Segments

Delving more deeply into the results of the 6-month-old infants provides some interesting insights into the sequential nature of the acquisition of native-language segments. Recall that 6-month-old infants discriminated the fricative contrast in all spectral tilt conditions, and the highest DI was found in the Positive Tilt condition. In the case of approximants, 6-month-olds discriminated the contrast in the Normal Speech and Positive Tilt conditions, and finally for vowels, discrimination was observed in the Negative Tilt condition, although best performance was in the Normal Speech condition.

The above pattern of results might be attributable to the earlier emergence of perceptual reorganisation for vowels compared to consonants. That is, because infants begin to acquire native vowels prior to consonants (Kuhl et al., 1992; Polka & Werker, 1994) the 6-month-olds in this study might be showing signs that their vowel perception is becoming constrained by the specifics of native-language vowel categories. This would explain why in the vowel experiment (Experiment 3), the results for 6-month-olds are starting to resemble those for 9-month-olds, in that unmodified spectral tilt provided the best discrimination conditions. With fricatives, on the other hand, there was no evidence that 6-month-olds had attuned to the native spectral profiles of /f/ and /s/ because they discriminated the contrast in all three spectral tilt conditions, and the best DI was in the Positive Tilt, not the Normal Speech, condition.

This explanation might also be applied to the results for approximants (Experiment 2). Approximants are often regarded as semi-vowels because of their characteristic formant structures and vowel-like articulation (Harrington & Cassidy, 1999) and hence can be thought of as lying somewhere between true consonants and true vowels. In this series of experiments, like vowels, the approximants were discriminable in only two of the three tilt conditions: Normal Speech and Positive Tilt, which emphasised the relevant region of the speech spectrum, and discrimination performance was equivalent in the two conditions. Taken together, the results suggest that younger infants have made some progress in the acquisition of native-language categories for vowels, and perhaps even approximants. Furthermore, it is suggested that 6-month-olds will soon reach the stage whereby modified spectral tilt hinders discrimination, and the results indicate that this will happen first for vowels, then approximants, and then fricatives.

11.4 Implications for HI Infants

Because the three experiments reported here investigated speech perception in NH infants, the main implications of this work are necessarily limited to the development of NH infants' speech perception. However, the original motivation for this research project was to examine whether a particular spectral tilt provided optimal speech intelligibility for NH infants, with a view to improving the efficacy of amplification provided to HI infants. Although for 9-month-olds, unmodified spectral tilt was clearly optimal, no single spectral tilt was identified as optimal for 6-month-olds. Clearly this research is too preliminary to have direct implications regarding infants' hearing aids. However, the newfound knowledge about NH infants' perception of acoustically modified speech does have implications for the development of language in HI children, particularly their attunement to and acquisition of native-language speech categories.

11.4.1 Native-language Attunement in HI infants

11.4.1.1 Behavioural Measures of Speech Development

This thesis has outlined various behavioural studies which show how NH infants' speech perception and production transforms from a language-general to a language-specific mode as their experience with the native language takes effect. In other words, infants 'attune' to their native language. That is, perception of the segmental (Polka et al., 2001) and suprasegmental (Jusczyk et al., 1992) features of the native language improves while perception of non-native sounds declines (Best & McRoberts, 2003; Werker & Tees, 1984). Similarly, infants' vocal productions exhibit more native-language suprasegmental and segmental elements at the expense of non-native sound patterns (De Boysson-Bardies & Vihman, 1991; Whalen et al., 2007; Whalen et al., 1991). Importantly, there is recent evidence showing that if infants' language perception does not show progressive attunement to the native language this may have a detrimental effect on later language outcomes (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Rivera-Gaxiola, Klarman, Adrian, & Kuhl, 2005a).

The role of native-language attunement in determining long-term language outcomes in both NH and HI children is an interesting issue. Often, studies of language development in HI infants and children comment on the high levels of variation created by individual differences (e.g., Moeller et al., 2007a; Moeller et al., 2007b; von Hapsburg & Davis, 2006). Usually, researchers look to socioeconomic factors, degree of HL, patterns of hearing aid use and quality of intervention to provide a potential explanation for the differences observed (Fitzpatrick et al., 2007; Yoshinaga-Itano, 2004). Although these factors are likely to play a role in determining language outcomes, another *key* factor in determining a HI infant's long-term language outcome is how closely their language development resembles that of NH infants, and specifically, whether their attunement to native speech progresses in the same manner and at the same rate as their NH peers. If, as Kuhl and colleagues (2008) suggest, NH infants have better language outcomes when they show robust native-language attunement (i.e., discriminate native contrasts better than non-native contrasts), then the same is also likely to hold true for HI infants. Thus, it is proposed that those HI infants who attune to the native language in a timely manner will be more likely to have better language outcomes than those who do not.

The crucial question is: Can HI infants attune to the native language in the same way that NH infants do? Since HI infants do not have access to the same language input as their NH counterparts, it may be that they attune to the native language later than NH infants, or they may never undergo perceptual reorganisation in a manner comparable to their NH peers. HI infants' less-than-ideal exposure to language is a result of several factors. To begin with, HI infants are deprived of exposure to auditory experiences for 3 months prenatally, and for the postnatal weeks until they are fitted with hearing aids. Although HI infants' access to speech improves markedly once hearing aids are fitted, it is still not equivalent to the experience of NH peers. This occurs for a variety of reasons. For instance, hearing aid use is often interrupted because of the constraints imposed by infant sleeping, feeding, and bathing routines. In addition, infant hearing-aid users often suffer from acoustic feedback due to amplification leakage which arises as young infants outgrow their earmolds as a result of rapid ear growth (Dillon, 2001; Gabbard & Schryer, 2003). Furthermore, the constraints of hearing aid technology and deficits associated with HL such as decreased frequency and temporal resolution mean that amplified speech input is always less than perfect (Dillon, 2001). Thus, although in most cases amplification is now provided very early in life, at no time do HI infants hear speech of the same quantity and quality that NH infants hear. This fact is likely to impact on the ability of HI infants to attune to their native language in the same manner as NH infants.

As yet, no study has investigated whether HI infants attune to their native language. As a first step, young HI infants could be tested to see whether they discriminate their native language from others on the basis of suprasegmental cues. Such experiments would tell us whether the speech input HI infants hear is of sufficient quality to transmit the suprasegmental features of their native language – features that NH infants so readily attend to in the early months of life (Mehler et al., 1988; Nazzi et al., 1998). Given that NH infants' perception of the suprasegmental features of speech seems to be a necessary precursor to later segmental perception, it would seem vital that HI infants recognise the suprasegmental details of their native language as early as possible.

Following studies that establish whether or not HI infants recognise their native language, the next step would be to compare HI infants' perception of native and non-native speech contrasts. Such tests would provide valuable information about whether HI infants attune to native-language segments, and in particular, whether their discrimination of non-native contrasts declines. Ideally, testing would be conducted at various ages from 4 to 24 months, perhaps using the CHT method that has been developed for use with HI infants (Eisenberg et al., 2007; Fredrickson & Uhler, 2006; Martinez et al., 2008). Testing HI infants as young as 4 months is likely to be difficult (Eisenberg et al., 2007; Martinez et al., 2008) so it might be more realistic to test infants at 4 months post-amplification rather than post-birth. Testing infants as old as 24 months is considered necessary because it allows for the possibility that attunement to native-language speech categories will be significantly delayed in HI infants.

An assessment of HI infants' non-native segment perception has the potential to be an effective means of pinpointing HI infants' *stage* of language acquisition. That is, if HI infants' discrimination of non-native vowels and consonants declines at 6 and 9 months of age respectively, this would suggest that HI infants attune to the native language and undergo perceptual reorganisation at the same rate as NH infants. However, a more likely outcome is that HI infants' attunement to the native language will be delayed compared to that of NH infants. A third, but less likely, possibility is that perceptual reorganisation will not be observed in HI infants, suggesting that congenital hearing impairment results in speech perception that is fundamentally different from that of NH listeners.

Production studies also have the potential to provide knowledge of HI infants' attunement to the native language. Recent research has suggested that, in general, early-identified HI infants' speech production is delayed, although qualitatively similar to that of NH infants (Moeller et al., 2007a; Moeller et al., 2007b). These results could be extended by conducting detailed acoustic comparisons of HI and NH infants' consonants and vowels to examine whether HI infants' utterances resemble those of NH infants and gravitate towards the native language. Recently, McGowan et al. (2008) compared the F1-F2 vowel spaces of NH and HI 12-month-olds and found that although the vowels of both groups were similar in terms of F1, the HI infants' F2 range was more restricted than that of the NH infants. However, to date, no production studies have examined whether HI infants' vowels become more native-like as experience of language accumulates. We know that NH infants' vowels become increasingly language-specific over time (De Boysson-Bardies et al., 1989; Rvachew et al., 2006) and if HI infants were to show a similar pattern, this would constitute evidence of native-language attunement. Similarly, if production studies were conducted on HI infants from two or more language groups, the resultant cross-language comparisons would provide valuable information about whether and when the babbling of HI infants starts to become more language-specific.

11.4.1.2 Neural Correlates of Speech Development

In order to gain a more complete understanding of native-language attunement in HI infants, it is necessary to examine the neural structures and processes which underpin behavioural demonstrations of perceptual reorganisation in the speech domain. Studies are needed to investigate whether impoverished auditory experience results in neural auditory pathways that preclude 'normal' native-language attunement. In NH infants, ERP and brain imaging studies are increasingly providing evidence of the neural substrates of attunement. As outlined in section 3.3.2, cortical responses to phonemic versus non-phonemic vowel contrasts become highly differentiated as infants approach 12 months (Minagawa-Kawai et al., 2007), and MMN responses (which signal discrimination) are present for non-native contrasts at 6 to 7 months, but disappear by 11 to 12 months of age for both vowels (Cheour et al., 1998) and consonants (Rivera-Gaxiola et al., 2005b).

Just as researchers are starting to provide a clearer picture of what normal neural auditory pathways look like, evidence is also building that adequate early auditory experience is essential for the development of these pathways. To put it another way, abnormal auditory experience impairs neural auditory development. A significant auditory impairment such as sensorineural HL reduces nerve activity from the cochlea. This results in a lack of stimulation throughout the brain's auditory pathway and leads to widespread neural degeneration, including a reduction in synaptic density and neuronal shrinkage (Moore, 2002; Shepherd & Hardie, 2001; Syka, 2002). Moreover, studies of the development of the chinchilla auditory cortex suggest that inadequate auditory stimulation during early infancy disrupts the formation of neural connections that integrate spectral and temporal information (Pienkowski & Harrison, 2005). Even a unilateral congenital HL results in substantially altered neural activation patterns in response to sound (Scheffler, Bilecen, Schmid, Tschopp, & Seelig, 1998).

Although the adverse effects of impoverished auditory stimulation described above mean that a congenital HL is likely to result in abnormal neural pathways, there is also the flipside to be considered. What happens when auditory experience is enhanced after a period of auditory deprivation? Research indicates that enhanced auditory experience leads to beneficial changes in the auditory centres of the brain. By measuring auditory evoked responses in congenitally HI children fitted with hearing aids or cochlear implants, Sharma and colleagues have shown that atypical auditory pathways can recover and produce responses within normal range, with better outcomes found in those with less severe losses and an earlier age of auditory stimulation (Sharma, Dorman, & Spahr, 2002; Sharma et al., 2005). Although this research is mostly promising, much of it has been conducted with cochlear implant recipients and as such, it is still not clear whether the auditory stimulation provided by hearing aids is of sufficient quality to restore neural auditory function such that infants maintain their ability to discriminate native speech contrasts and show a decline in their ability to discriminate non-native speech contrasts. Clearly, there is much research to be done in this area, both in the behavioural and neural spheres in order to discover whether, when, and how native-language attunement might occur in HI infants.

11.4.2 Amplification Implications for HI Infants

If HI infants are to acquire their native language, it is likely that they will need, not only sufficient neural plasticity, but also ample exposure to spectrally complete native-language speech. To achieve this, hearing aid amplification schemes would need to preserve the segmental and suprasegmental characteristics of the language with minimal distortion. In other words, the amplification strategy should mimic the spectral shape of natural speech, insofar as this is possible given bandwidth and other limitations of hearing aids. Importantly, the type of amplification implicated here is already being provided by the current DSL and NAL infant amplification strategies, both of which, despite their different approaches, maintain the basic shape of the LTASS. Thus, perhaps the most important challenges in the future will be to increase hearing aid bandwidths and enhance signal processing to allow for the speech spectrum to be transmitted in its entirety, and thus provide HI infants with the opportunity to perceive spectrally intact native speech.

Of particular relevance here is a new method of signal processing that aims to preserve the spectral characteristics of high-frequency speech sounds, such as fricatives. Known as nonlinear frequency compression (NFC), this method seeks to overcome hearing aid bandwidth limitations by taking the high-frequency region of the speech spectrum and compressing it by a pre-determined ratio, leaving the lower frequencies intact (Bagatto, 2008; Scollie et al., under review). This technology shows promise in terms of providing listeners with greater access to high-frequency information and in turn, improving listeners' production of high-frequency consonants (Polonenko et al., 2007). One of the advantages of NFC is that, although the shape of the spectrum may be somewhat compromised, its natural tilt is maintained and therefore, NFC may prove to be a particularly efficacious method for providing spectral completeness.

11.4.3 Speech Input for HI infants

One of this study's key findings is that the discrimination performance of younger NH infants improves when modified spectral tilt emphasises frequency information relevant to the particular speech contrast. Thus, it might be the case that HI infants would also benefit from exposure to speech sounds in which the acoustic differences between sounds are emphasised. If positive or negative spectral tilt or other acoustic adjustments were applied to speech sounds to highlight the crucial differences between them (e.g., frication noise, or a formant transition, or vowel length), this might assist HI infants to discriminate and identify native-language sounds. Relevant acoustic modifications could be applied to certain speech sounds during intervention sessions with young infants, and if it could be shown that this led to an improvement in an infant's production and perception of native speech sounds, then this method could potentially become a valuable training tool in intervention programs.

There is encouraging evidence from NH children with language-learning impairment (LLI) that auditory training using acoustically modified speech can improve speech discrimination and language processing (Tallal et al., 1996). In this study, two groups of LLI children aged between 5 and 10 years underwent a month of intensive one-on-one language and auditory training in which they completed pre-recorded language exercises and computer games. For one group, the materials were acoustically modified by first increasing the duration by 50% and then enhancing rapid frequency changes (such as formant transitions) by up to 20dB. These modifications were designed to make the differences between sounds more salient. A second group was trained using the same materials, but presented as natural speech. Comparison of pre- and post-training test results showed that the group exposed to the acoustically modified speech dramatically improved their speech discrimination and language comprehension immediately after training, and the improvement was maintained at a second post-training test administered six weeks later.

The thesis findings, and those of Tallal et al. (1996) showing that infants and children are responsive to enhanced or exaggerated linguistic features brings to mind IDS. In IDS, the differences between speech sounds are highlighted by the speaker rather than by artificial means. The vowels, tones and consonants of IDS are typically exaggerated (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2007); and there is some evidence that these exaggerated vocalisations facilitate language learning in infants (Burnham et al., 2002) and that infants of mothers who hyperarticulate vowels are better at discriminating speech sounds generally (Liu et al., 2003). Although the exact role IDS plays in language learning is yet to be resolved, it is difficult to ignore the potential usefulness of naturally occurring hyperarticulation for HI infants. The results of this thesis suggest that younger HI infants, in particular, might benefit from exposure to hyperarticulated segments. The fact that IDS is used by mothers of deaf infants, and that it is more similar to IDS for experience-matched, rather than age-matched, NH children (Bergeson et al., 2006) suggests that parents may have an unconscious awareness of its usefulness. However, in general, mothers of HI infants are less responsive to their infants than are mothers of NH infants (Cheskin, 1981; Henggeler & Cooper, 1983) and thus it might be beneficial if parents (and other adults) were encouraged to deliberately emphasise differences between sounds by using IDS in a particularly exaggerated and prolonged way when talking to HI infants.

11.5 Conclusions

The findings presented in this thesis show that 6- and 9-month-old infants differ in their ability to perceive speech with modified spectral tilt. Younger infants are able to discriminate a range of spectrally tilted speech contrasts and benefit when the tilt emphasises relevant acoustic information. Nine-month-olds, on the other hand, have consistently shown that they can only discriminate speech contrasts in which the spectral shape is unmodified. Because the speech contrasts were carefully selected to be representative of sounds across the speech spectrum, it seems to be the case that older infants are incapable of discriminating spectrally tilted speech contrasts, regardless of their frequency characteristics. Thus, for the first time, an acoustic modification has been shown to interfere with native speech discrimination by 9-month-old infants who are in an intense period of native-language attunement and perceptual reorganisation. With the advent of new brain imaging techniques, the importance of native-language attunement in the NH population is starting to be more fully appreciated, and it is now time to address the issue in HI infants too. It is necessary to examine (i) whether HI infants attune to the native language in the same manner; and (ii) at the same rate as NH infants; and (iii) whether HI infants' neural infrastructure is capable of supporting such attunement.

If it is found that native-language attunement can and does occur in HI infants in a manner comparable to that found in NH infants, then the results reported here suggest a number of implications for HI infants. Firstly, to assist HI infants to achieve native-language attunement, the natural spectral profile of speech should be preserved via amplification schemes. Additionally, in order to take advantage of younger infants' pre-attunement perceptual flexibility, parents of HI infants could be encouraged to provide HI infants with access to hyperarticulated speech segments through IDS. This could be complemented by more formal training for HI infants in recognising acoustically modified native speech sounds to facilitate the acquisition of native-language segments. If behavioural and neural attunement to the native language is the hallmark of normal language development, then any progress made towards identifying and facilitating HI infants' attunement capabilities will take us a step closer to ensuring that language outcomes for infant HI infants are as good as they can be.

REFERENCES

Abercrombie, D. (1967). *Elements of general phonetics*. Edinburgh: University of Edinburgh Press.

Agung, K., Purdy, S. C., & Kitamura, C. (2005). The Ling Sound Test revisited. *The Australian and New Zealand Journal of Audiology, 27*(1), 33-41.

Allen, T. E. (1986). Patterns of academic achievement among hearing impaired students: 1974 and 1983. In A. Schildroth & A. M. Karchmer (Eds.), *Deaf children in America* (pp. 161-206). Boston, MA: College-Hill Press.

Apuzzo, M. L., & Yoshinaga-Itano, C. (1995). Early identification of infants with significant hearing loss and the Minnesota Child Development Inventory. *Seminars in Hearing, 16*, 124–139.

Armitage, S. E., Baldwin, B. A., & Vince, M. A. (1980). The fetal sound environment of sheep. *Science, 208*, 1173-1174.

Arterberry, M. E., & Bornstein, M. H. (2002). Variability and its sources in infant categorization. *Infant Behavior and Development, 25*, 515-528.

Aslin, R. N. (1989). Discrimination of frequency transitions by human infants. *Journal of the Acoustical Society of America, 86*, 582-590.

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

Aslin, R. N., & Smith, J. (1988). Perceptual development. *Annual Review of Psychology, 39*, 435-473.

Bagatto, M. (2008, June). *Outcomes of nonlinear frequency compression in listeners with high frequency hearing loss*. Paper presented at the Phonak Satellite Event at the Newborn Hearing Screening Conference, Como, Italy.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology, 36*(2), 190-201.

Bergeson, T. R., Miller, R. J., & McCune, K. (2006). Mothers' speech to hearing-impaired infants and children with cochlear implants. *Infancy, 10*(3), 221-240

Bernard, J. (1970). Toward the acoustic specification of Australian English. *Zeitschrift fur Phonetik, Sprachwissenschaft und Kommunikationsforschung, 23*, 113-128.

Bernstein Ratner, N. (1984). Patterns of vowel modification in mother-child speech. *Journal of Child Language, 11*, 557-578.

Bernstein Ratner, N., & Luberoff, A. (1984). Cues to post-vocalic voicing in mother-child speech. *Journal of Phonetics, 12*, 285-289.

Bertenthal, B. I., Haith, M. M., & Campos, J. J. (1983). The partial-lag design: A method for controlling spontaneous regression in the infant-control habituation paradigm. *Infant Behavior and Development, 6*(2-3), 331-338.

Bertoncini, J., Bijeljac-Babic, R., Blumstein, S. E., & Mehler, J. (1987). Discrimination in neonates of very short CVs. *Journal of the Acoustical Society of America, 82*(1), 31-37.

Bess, F. H., & Paradise, J. L. (1994). Universal screening for infant hearing impairment: Not simple, not risk-free, not necessarily beneficial, and not presently justified. *Pediatrics, 93*, 330-334.

Best, C. T. (1995). A direct realist view of cross-language speech perception. In W. Strange & J. J. Jenkins (Eds.), *Speech perception and linguistic experience* (pp. 171-204). Timonium, MD: York Press.

Best, C. T., & Jones, C. (1998). Stimulus-alternation preference procedure to test infant speech discrimination. *Infant Behavior and Development, 21*(Special Issue), 295.

Best, C. T., & McRoberts, G. W. (2003). Infant perception of non-native consonant contrasts that adults assimilate in different ways. *Language and Speech, 46*(2-3), 183-216.

Best, C. T., McRoberts, G. W., LaFleur, R., & Silver-Isenstadt, J. (1995). Divergent developmental patterns for infants' perception of two nonnative consonant contrasts. *Infant Behavior and Development, 18*(3), 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*(3), 345-360.

Bijeljac-Babic, R., Bertoncini, J., & Mehler, J. (1993). How do 4-day-old infants categorize multisyllabic utterances? *Developmental Psychology, 29*(4), 711-721.

Birnholz, J. C., & Benacerraf, B. R. (1983). The development of human fetal hearing. *Science, 222*, 516-518.

Blamey, P. J., Sarant, J. Z., Paatsch, L. E., Barry, J. G., Bow, C. P., Wales, R. J., et al. (2001). Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing. *Journal of Speech, Language, and Hearing Research, 44*, 264-285.

Boersma, P., & Weenink, D. (2005). Praat: Doing Phonetics by Computer (Version 4.4.16) [Computer program]. Retrieved March, 2006, from http://www.praat.org/.

Bohn, O.-S. (2007). *Exploring the natural referent vowel hypothesis in perception experiments with Danish-learning infants.* Paper presented at the 153rd Meeting of the Acoustical Society of America, Salt Lake City.

Bohn, O.-S., & Polka, L. (2001). Target spectral, dynamic spectral, and duration cues in infant perception of German vowels. *Journal of the Acoustical Society of America, 110*, 504-515.

Bond, Z. S., Petrosino, L., & Dean, C. R. (1982). The emergence of vowels: 17 to 26 months. *Journal of Phonetics, 10*, 417-422.

Bosch, L., & Sebastián-Gallés, N. (2003). Simultaneous bilingualism and the perception of a language-specific vowel contrast in the first year of life. *Language and Speech, 46*, 217-243.

Bredberg, G. (1985). The anatomy of the developing ear. In S. E. Trehub & B. Schneider (Eds.), *Auditory Development in Infancy* (Vol. 10, pp. 3-20). New York: Plenum Press.

Bryant, G. A., & Barrett, H. C. (2007). Recognizing intentions in infant-directed speech: Evidence for universals. *Psychological Science, 18*(8), 746-751.

Buhr, R. D. (1980). The emergence of vowels in an infant. *Journal of Speech and Hearing Research, 23*, 62-94.

Bull, D., Eilers, R. E., & Oller, D. K. (1984). Infants' discrimination of intensity variation in multisyllabic stimuli. *Journal of the Acoustical Society of America, 76*(1), 13-17.

Burnham, D. (1986). Developmental loss of speech perception: Exposure to and experience with a first language. *Applied Psycholinguistics, 7*, 207-240.

Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2002). What's new, pussycat? On talking to babies and animals. *Science, 296*(5572), 1435.

Butcher, A. (2006). *Formant frequencies of /hVd/ vowels in the speech of South Australian females.* Paper presented at the 11th Australian International Conference on Speech Science & Technology, Auckland.

Byrne, D., Dillon, H., Tran, K., Arlinger, S., Wilbraham, K., Cox, R., et al. (1994). An international comparison of long-term average speech spectra. *Journal of the Acoustical Society of America, 96*(4), 2108-2120.

Byrne, D., & Tonisson, W. (1976). Selecting the gain of hearing aids for persons with sensorineural hearing impairments. *Scandinavian Audiology, 5*, 51-59.

Caramazza, A., & Yeni-Komshian, G. H. (1974). Voice onset time in two French dialects. *Journal of Phonetics, 2*, 239-245.

Carney, A. (1986). Understanding speech intelligibility in the hearing impaired. *Topics in Language Disorders, 6*(3), 47-59.

Cheour, M., Ceponiene, R., Lehtokovski, A., Luuk, A., Allik, J., Alho, K., et al. (1998). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience, 1*(5), 351-353.

Cheskin, A. (1981). The verbal environment provided by hearing mothers for their young deaf children. *Journal of Communication Disorders, 14*, 485-496.

Ching, T. Y. C. (2003). Selecting, verifying, and evaluating hearing aids for children. *Audiological Medicine, 1*, 191-198.

Ching, T. Y. C., Britton, L., Dillon, H., & Agung, K. (2002). RECD, REAG, NAL-NL1: Accurate and practical methods for fitting non-linear hearing aids to infants and children. *Hearing Review, 9*(8), 12-20.

Ching, T. Y. C., Dillon, H., & Byrne, D. (1998). Speech recognition of hearing-impaired listeners: Predictions from audibility and the limited role of high-frequency amplification. *Journal of the Acoustical Society of America, 103*, 1028-1140.

Ching, T. Y. C., Dillon, H., Katsch, R., & Byrne, D. (2001). Maximizing effective audibility in hearing aid fitting. *Ear and Hearing, 22*(3), 212-224.

Ching, T. Y. C., van Wanrooy, E., Skinner, L., Crowe, K., Day, J., Close, L., et al. (2007, July). *Speech and language development of hearing-impaired infants and children*. Paper presented at the XVth Biennial Conference of the Australasian Human Development Association, Sydney.

Christophe, A., Dupoux, E., Bertoncini, J., & Mehler, J. (1994). Do infants perceive word boundaries? An empirical study of the bootstrapping of lexical acquisition. *Journal of the Acoustical Society of America, 95*(3), 1570-1580.

Christophe, A., Mehler, J., & Sebastián-Gallés, N. (2001). Perception of prosodic boundary correlates by newborn infants. *Infancy, 2*(3), 385-394.

Clark, J., & Yallop, C. (1990). *An introduction to phonetics and phonology*. Oxford: Basil Blackwell.

Clarkson, M. G. (1996). Infants' intensity discrimination: Spectral profiles. *Infant Behavior and Development, 19*, 181-190.

Clarkson, M. G., Clifton, R. K., & Perris, E. (1988). Infant timbre perception: Discrimination of spectral envelopes. *Perception and Psychophysics, 43*, 15-20.

Clement, C. J., Koopmans-van Beinum, F. J., & Pols, L. C. W. (1996, October). *Acoustical characteristics of sound production of deaf and normally hearing infants.* Paper presented at the 4th International Conference on Spoken Language Processing, Philadelphia.

Coates, H., & Gifkins, K. (2003). Newborn hearing screening. *Australian Prescriber, 26*(4), 82-84.

Cohen, L. B. (1969). Observing responses, visual preferences, and habituation to visual stimuli in infants. *Journal of Experimental Child Psychology, 7*, 419-433.

Cohen, L. B. (2004). Uses and misuses of habituation and related preference paradigms. *Infant and Child Development, 13*(4), 349-352.

Cohen, L. B., DeLoache, J. S., & Rissman, M. W. (1975). The effect of stimulus complexity on infant visual attention and habituation. *Child Development, 46*, 611–617.

Cole, R. A., & Jakimik, J. (1980). A model of speech perception. In R. A. Cole (Ed.), *Perception and production of fluent speech* (pp. 133-163). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cornelisse, L. E., Seewald, R. C., & Jamieson, D. G. (1995). The input/output formula: A theoretical approach to the fitting of personal amplification devices. *Journal of the Acoustical Society of America, 97*, 1854-1864.

Cox, F. (1996). *An acoustic analysis of vowel variation in Australian English.* Unpublished doctoral dissertation, Macquarie University, Sydney.

Cox, F. (2006). The Acoustic characteristics of /hVd/ vowels in the speech of some Australian teenagers. *Australian Journal of Linguistics, 26*, 147-179.

Crade, M., & Lovett, S. (1988). Fetal response to sound stimulation: Preliminary report exploring use of sound stimulation in routine obstetrical ultrasound examinations. *Journal of Ultrasound in Medicine, 7*, 499-503.

Cruttenden, A. (1986). *Intonation*. Cambridge: Cambridge University Press.

Crystal, D. (1969). *Prosodic systems and intonation in English*. Cambridge: Cambridge University Press.

Cutler, A. (1994). Segmentation problems, rhythmic solutions. *Lingua, 92*, 81-104.

Cutler, A., & Carter, D. M. (1987). The predominance of strong initial syllables in the English vocabulary. *Computer Speech and Language, 2*, 133-142.

Cutler, A., & Mehler, J. (1993). The periodicity bias. *Journal of Phonetics, 21*, 103-108.

Cutler, A., Mehler, J., Norris, D. G., & Segui, J. (1986). The syllable's differing role in the segmentation of French and English. *Journal of Memory and Language, 25*, 385-400.

Davis, J. M., Elfenbein, J., Schum, R., & Bentler, R. A. (1986). Effects of mild and moderate hearing Impairments on language, educational, and psychosocial behavior of children. *Journal of Speech and Hearing Disorders, 51*, 53-62.

De Boysson-Bardies, B., Halle, L., Sagart, P., & Durand, C. (1989). A cross-linguistic investigation of vowel formants in babbling. *Journal of Child Language, 16*, 1-17.

De Boysson-Bardies, B., Sagart, L., & Durand, C. (1984). Discernible differences in the babbling of infants according to target language. *Journal of Child Language, 11*(1), 1-15.

De Boysson-Bardies, B., & Vihman, M. M. (1991). Adaptation to language: Evidence from babbling and first words in four languages. *Language, 67*(2), 297-339.

DeCasper, A. J., & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mother's voice. *Science, 208*, 1174-1176.

DeCasper, A. J., & Prescott, P. A. (1984). Human newborns' perception of male voices: Preference, discrimination and reinforcing value. *Developmental Psychobiology, 17*, 481-491.

DeCasper, A. J., & Spence, M. J. (1986). Prenatal maternal speech influences newborns' perception of speech sounds. *Infant Behavior and Development, 9*, 133-150.

Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science, 298*(5600), 2013-2015.

Delattre, P. C. (1961). La lecon d'intonation de Simone de Beauvoir, etude d'intonation declarative comparee. *The French Review, 35*, 59-67.

Delattre, P. C. (1965). *Comparing the phonetic features of English, German, Spanish, and French*. Heidelberg: Julius Groos.

Delattre, P. C., Liberman, A. M., & Cooper, F. S. (1951). Voyelles synthetiques a deux formantes et voyelles cardinales. *Maitre Phonetique, 96*, 30-36.

Dillon, H. (1999). NAL-NL1: A new prescriptive fitting procedure for non-linear hearing aids. *The Hearing Journal, 52*(4), 10-16.

Dillon, H. (2001). *Hearing Aids*. Sydney: Boomerang Press.

Durieux-Smith, A., & Whittingham, J. (2000). The rationale for neonatal hearing screening. *Journal of Speech Language Pathology and Audiology, 24*, 59-67.

Eggermont, J. J., Brown, D. K., Ponton, C. W., & Kimberley, B. P. (1996). Comparison of distortion product otoacoustic emission (DPOAE) and auditory brain stem response (ABR) traveling wave delay measurements suggests frequency-specific synapse maturation. *Ear and Hearing, 17*, 386-394.

Eilers, R. E. (1977). Context-sensitive perception of naturally produced stops and fricative consonants by infants. *Journal of the Acoustical Society of America, 61*, 1321–1336.

Eilers, R. E., & Oller, D. K. (1994). Infant vocalizations and the early diagnosis of severe hearing impairment. *Journal of Pediatrics, 124*(2), 199-203.

Eilers, R. E., Oller, D. K., & Benito-Garcia, C. R. (1984). The acquisition of voicing contrasts in Spanish- and English-learning infants and children: A longitudinal study. *Journal of Child Language, 11*(2), 313-336.

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

Eimas, P. D. (1975). Auditory and phonetic coding of the cues for speech: Discrimination of the [r-l] distinction by young infants. *Perception and Psychophysics, 18*(5), 341-347.

Eimas, P. D., Siqueland, E. R., Jusczyk, P. W., & Vigorito, J. (1971). Speech perception in infants. *Science, 171*, 303-306.

Eisenberg, L. S., Martinez, A. S., & Boothroyd, A. (2007). Assessing auditory capabilities in young children. *International Journal of Pediatric Otorhinolaryngology 71*, 1339-1350.

Elfenbein, J. L., Hardin-Jones, M. A., & Davis, J. M. (1994). Oral communication skills of children who are hard of hearing. *Journal of Speech and Hearing Research, 37*, 216-226.

Englund, K. T. (2005). Voice onset time in infant directed speech over the first six months. *First Language, 25*(2), 219-234.

Engstrand, O., Williams, K., & Lacerda, F. (2003). Does babbling sound native? Listener responses to vocalizations produced by Swedish and American 12- and 18-month-olds. *Phonetica, 60*(1), 17-44.

Fantz, R. L. (1963). Pattern Vision in Newborn Infants. *Science, 140*(3564), 296-297.

Ferguson, C. A. (1964). Baby talk in six languages. *American Anthropologist, 66*, 103-114.

Fernald, A. (1985). Four-month-old infants prefer to listen to motherese. *Infant Behavior and Development, 8*, 181-195.

Fernald, A. (1989). Intonation and communicative intent in mothers' speech to infants: Is the melody the message? *Child Development, 60*(6), 1497-1510.

Fernald, A. (1992). Meaningful melodies in mothers' speech to infants. In H. Papousek, U. Jurgens & M. Papousek (Eds.), *Nonverbal vocal behaviour*. New York: Cambridge University Press.

Fernald, A. (1993). Approval and disapproval: Infant responsiveness to vocal affect in familiar and unfamiliar languages. *Child Development, 64*, 657-674.

Fernald, A., & Kuhl, P. K. (1987). Acoustic determinants of infant preference for motherese speech. *Infant Behavior and Development, 10*, 279-293.

Fernald, A., & Morikawa, H. (1993). Common themes and cultural variations in Japanese and American mothers' speech to infants. *Child Development, 64*, 637-656.

Fernald, A., & Simon, T. (1984). Expanded intonation contours in mothers' speech to newborns. *Developmental Psychology, 20*(1), 104-113.

Fernald, A., Taeschner, T., Dunn, J., Papousek, M., de Boysson-Bardies, B., & Fukui, I. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language, 16*, 477-501.

Fitzpatrick, E., Durieux-Smith, A., Eriks-Brophy, A., Olds, J., & Gaines, R. (2007). The impact of newborn hearing screening on communication development. *Journal of Medical Screening, 14*(3), 123-131.

Fletcher, J. (1991). Rhythm and final lengthening in French. *Journal of Phonetics, 19*(2), 193-212.

Fortnum, H. M., Summerfield, A. Q., Marshall, D. H., Davis, A. C., & Bamford, J. M. (2001). Prevalence of permanent childhood hearing impairment in the United Kingdom and implications for universal neonatal hearing screening: Questionnaire based ascertainment study. *British Medical Journal, 323*, 536-540.

Fredrickson, T., & Uhler, K. (2006, April). *Infant speech discrimination and hearing loss*. Paper presented at the American Academy of Audiology National Convention, Minneapolis.

Friederici, A. D., & Wessels, J. M. (1993). Phonotactic knowledge of word boundaries and its use in infant speech perception. *Perception and Psychophysics, 54*(3), 287-295.

Gagnon, R., Benzaquen, S., & Hunse, C. (1992). The fetal sound environment during vibroacoustic stimulation in labor: Effect on fetal heart rate response. *Obstetrics and Gynecology, 79*(6), 950-955.

Garde, P. (1968). *L'accent*. Paris: Presses Universitaires de France.

Geers, A., & Moog, J. (1989). Factors predictive of the development of literacy in profoundly hearing-impaired adolescents. *Volta Review, 91*(2), 69-86.

Gelfand, S. A. (1998). *Hearing: An introduction to psychological and phsyiological acoustics* (3rd ed.). New York: Marcel Dekker.

Gerhardt, K. J., & Abrams, R. M. (2000). The fetus: Fetal exposures to sound and vibroacoustic stimulation. *Journal of Perinatology, 20*, S20-S29.

Gerhardt, K. J., Abrams, R. M., & Oliver, C. C. (1990). Sound environment of the fetal sheep. *American Journal of Obstetrics and Gynecology, 162*(1), 282-287.

Gerhardt, K. J., Otto, R., Abrams, R. M., Colle, J. J., Burchfield, D. J., & Peters, A. J. (1992). Cochlear microphonics recorded from fetal and newborn sheep. *American Journal of Otolaryngology, 13*(4), 226-233.

Glennon, S. (2008, May). *The Queensland Healthy Hearing Program*. Paper presented at the Fifth National Deafness Sector Summit, Canberra.

Griffiths, S. K., Brown, W. S., Gerhardt, K. J., Abrams, R. M., & Morris, R. J. (1994). The perception of speech sounds recorded within the uterus of a pregnant sheep. *Journal of the Acoustical Society of America, 96*, 2055-2063.

Halle, P. A., De Boysson-Bardies, B., & Vihman, M. M. (1991). Beginnings of prosodic organization: Intonation and duration patterns of disyllables produced by Japanese and French infants. *Language and Speech, 34*(4), 299-318.

Halliday, M. A. K. (1970). *A course in spoken English: Intonation*. London: Edward Arnold.

Harrington, J., & Cassidy, S. (1999). *Techniques in speech acoustics*. Dordecht: Kluwer Academic.

Harrington, J., Cox, F., & Evans, Z. (1997). An acoustic phonetic study of broad, general and cultivated Australian English vowels. *Australian Journal of Linguistics, 17*, 155-184.

Hauser, M. D., Newport, E. L., & Aslin, R. N. (2001). Segmentation of the speech stream in a nonhuman primate: Statistical learning in cotton-top tamarins. *Cognition, 78*, B53-B64.

Hayashi, A., Tamekawa, Y., & Kiritani, S. (2001). Developmental change in auditory preferences for speech stimuli in Japanese infants. *Journal of Speech, Language, and Hearing Research, 44*, 1189-1200.

Henggeler, S. W., & Cooper, P. F. (1983). Deaf child-hearing mother interaction: Extensiveness and reciprocity. *Journal of Pediatric Psychology, 8*, 83-95.

Hepper, P. G. (1991). An examination of fetal learning before and after birth. *Irish Journal of Psychology, 12*, 95-107.

Hepper, P. G., & Shahidullah, S. (1994). Development of fetal hearing. *Fetal and Maternal Medicine Review, 6*, 167-179.

Hillenbrand, J. (1984). Speech perception by infants: Categorization based on nasal consonant place of articulation. *Journal of the Acoustical Society of America, 75*(5), 1613-1622.

Hirsh-Pasek, K., Kemler Nelson, D. G., Jusczyk, P. W., Cassidy, K. W., Druss, B., & Kennedy, L. (1987). Clauses are perceptual units for young infants. *Cognition, 26*(3), 269-286.

Hoequist, C. (1983). Syllable duration in stress-, syllable- and mora-timed languages. *Phonetica 40*, 203-237.

Hogan, C. A., & Turner, C. W. (1998). High-frequency audibility: Benefits for hearing-impaired listeners. *Journal of the Acoustical Society of America, 104*(1), 432-441.

Holmberg, T. L., Morgan, K. A., & Kuhl, P. K. (1977). Speech perception in early infancy: Discrimination of fricative consonants. *Journal of the Acoustical Society of America, 62* (Supp. No.1), S99.

Houston, D., Pisoni, D. B., Kirk, K. I., Ying, E. A., & Miyamoto, R. T. (2003). Speech perception skills of deaf infants following cochlear implantation: A first report. *International Journal of Pediatric Otorhinolaryngology, 67*(5), 479-495.

Houston, D. M., Horn, D. L., Qi, R., Ting, J. Y., & Gao, S. (2007). Assessing speech discrimination in individual infants. *Infancy, 12*, 119-145.

Howell, D. C. (2007). *Statistical methods for psychology* (6th ed.). Belmont, CA: Thomson Wadsworth.

Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology, 387*, 167-178.

Hyde, M. L. (2005). Newborn hearing screening programs: Overview. *The Journal of Otolaryngology, 34*(Supplement 2), S70-S78.

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

Jeffrey, W. B., & Cohen, L. B. (1971). Habituation in the human infant. In H. Reese (Ed.), *Advances in child development and behavior* (Vol. 6, pp. 63-97). New York: Academic Press.

Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English fricatives. *Journal of the Acoustical Society of America, 108*(3), 1252-1263.

Jusczyk, P. W. (1989, April). *Perception of cues to clausal units in native and non-native languages.* Paper presented at the Biennial Meeting of the Society for Research in Child Development, Kansas City, MO.

Jusczyk, P. W. (2003). American infants' perception of cues to grammatical units in non-native languages and music: Evidence from Polish and Japanese. In D. Houston, A. Seidl, G. Hollich, E. Johnson & A. M. Jusczyk (Eds.), *Jusczyk Lab Final Report*: Retrieved from http://hincapie.psych.purdue.edu/Jusczyk.

Jusczyk, P. W., Copan, H., & Thompson, E. (1978). Perception by 2-month-old infants of glide contrasts in multisyllabic utterances. *Perception and Psychophysics, 24*(6), 515-520.

Jusczyk, P. W., Cutler, A., & Redanz, N. J. (1993a). Infants' preference for the predominant stress patterns of English words. *Child Development, 23*, 648-654.

Jusczyk, P. W., Friederici, A. D., Wessels, J. M., Svenkerud, V., & Jusczyk, A. M. (1993b). Infants' sensitivity to the sound patterns of native language words. *Journal of Memory and Language, 32*(3), 402-420.

Jusczyk, P. W., Hirsh-Pasek, K., Kemler Nelson, D. G., Kennedy, L. J., Woodward, A., & Piwoz, J. (1992). Perception of acoustic correlates of major phrasal units by young infants. *Cognitive Psychology, 24*(2), 252-293.

Jusczyk, P. W., Hohne, E. A., & Bauman, A. (1999a). Infants' sensitivity to allophonic cues for word segmentation. *Perception and Psychophysics, 61*(8), 1465-1476.

Jusczyk, P. W., Houston, D., & Newsome, M. (1999b). The beginnings of word segmentation in English-learning infants. *Cognitive Psychology, 39*(3-4), 159-207.

Jusczyk, P. W., & Kemler Nelson, D. G. (1996). Syntactic units, prosody, and psychological reality during infancy. In J. Morgan & K. Demuth (Eds.), *Signal to syntax: Bootstrapping from speech to grammar in early acquisition* (pp. 389-408). Cambridge, MA: MIT Press.

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*(5), 63-645.

Karzon, R. G. (1985). Discrimination of polysyllabic sequences by one- to four-month-old infants. *Journal of Experimental Child Psychology, 39*(2), 326-342.

Keefe, D. H., Bulen, J. C., Arehart, K. H., & Burns, E. M. (1993). Ear-canal impedance and reflection coefficient in human infants and adults. *Journal of the Acoustical Society of America, 94*(5), 2617-2638.

Keefe, D. H., & Levi, E. (1996). Maturation of the middle and external ears: Acoustic power-based responses and reflectance tympanometry. *Ear and Hearing, 17*(5), 361-373.

Kemler Nelson, D. G., Hirsh-Pasek, K., Jusczyk, P. W., & Cassidy, K. W. (1989). How the prosodic cues in motherese might assist language learning. *Journal of Child Language, 16*(1), 55-68.

Kennedy, C. R., McCann, D. C., Campbell, M. J., Kimm, L., & Thornton, R. (2005). Universal newborn screening for permanent childhood hearing impairment: An 8-year follow-up of a controlled trial. *The Lancet, 366*, 660-662.

Kennedy, C. R., McCann, D. C., Campbell, M. J., Law, C. M., Mullee, M., Petrou, S., et al. (2006). Language ability after early detection of permanent childhood hearing impairment. *The New England Journal of Medicine, 35*(4), 2131-2141.

Kent, R. D. (1981). Articulatory-acoustic perspectives on speech development. In R. E. Stark (Ed.), *Language behavior in infancy and early childhood*. New York: Elsevier-North Holland.

Kent, R. D., & Murray, A. D. (1982). Acoustic features of infant vocalic utterances at 3, 6 and 9 months. *Journal of the Acoustical Society of America 72*, 353-365.

Kent, R. D., Osberger, M. J., Netsell, R., & Goldschmidt Hustedde, C. (1987). Phonetic development in identical twins differing in auditory function. *Journal of Speech and Hearing Disorders 52*, 64-75.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition, 83*(2), B35-B42.

Kitamura, C., Beach, E. F., Dillon, H., Ching, T., & Burnham, D. (submitted). Infant preferences for spectral tilt. *Journal of Speech, Language, and Hearing Research*.

Kitamura, C., & Burnham, D. (1998). The infant's response to maternal vocal affect. In C. Rovee-Collier (Ed.), *Advances in infancy research* (Vol. 12, pp. 221-236). Norwood, NJ: Ablex.

Kitamura, C., & Burnham, D. (2003). Pitch and communicative intent in mothers' speech: Adjustments for age and sex in the first year. *Infancy, 4*(1), 85-110.

Kitamura, C., Dillon, H., Noble, W., Purdy, S. C., & Burnham, D. (accepted with revisions). Spectral tilt: Can infants tell the difference? *Ear and Hearing*.

Kitamura, C., & Lam, C. (2009). Age-specific preferences for infant-directed affective intent. *Infancy, 14*(1), 1-24.

Kitamura, C., & Notley, A. (accepted May 2008). The shift in infant preferences for vowel duration and pitch contour between 6 and 10 months of age. *Developmental Science*.

Kitamura, C., & Notley, A. (in press). The shift in infant preferences for vowel duration and pitch contour between 6 and 10 months of age. *Developmental Science*.

Kitamura, C., Thanavishuth, C., Burnham, D., & Luksaneeyanawin, S. (2002). Universality and specificity in infant-directed speech: Pitch modifications as a function of infant age and sex in a tonal and non-tonal language. *Infant Behavior and Development, 24*(4), 372-392.

Kopyar, B. A. (1997). *Intensity discrimination abilities of infants and adults: Implications for underlying processes.* Unpublished doctoral dissertation, University of Washington, Seattle.

Kortekaas, R. W. L., & Stelmachowicz, P. G. (2000). Bandwidth effects on children's perception of the inflectional morpheme /s/: Acoustical measurements, auditory detection, and clarity rating. *Journal of Speech, Language, and Hearing Research, 43*(3), 645-660.

Kruger, B. (1987). An update on the external ear resonance in infants and young children. *Ear and Hearing, 8*(6), 333-336.

Kuhl, P. K. (1983). Perception of auditory equivalence classes for speech in early infancy. *Infant Behavior and Development, 6*, 263-285.

Kuhl, P. K. (1991). Human adults and human infants show a "perceptual magnet effect" for prototypes of speech categories, monkeys do not. *Perception and Psychophysics, 50*(2), 93-107.

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, V. L., et al. (1997). Cross-language analysis of phonetic units in language addressed to infants *Science, 277*(5326), 684-686.

Kuhl, P. K., Conboy, B. T., Coffey-Corina, S., Padden, D., Rivera-Gaxiola, M., & Nelson, T. (2008). Phonetic learning as a pathway to language: New data and native language magnet theory expanded (NLM-e). *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363*, 979-1000.

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: Implications for the "critical period". *Language Learning and Development, 1*(3&4), 237-264.

Kuhl, P. K., & Meltzoff, A. N. (1996). Infant vocalizations in response to speech: Vocal imitation and developmental change. *Journal of the Acoustical Society of America, 100*, 2425-2438.

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science, 9*(2), F13-F21.

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.

Lacerda, F., & Sundberg, U. (2006). An ecological theory of language acquisition. *Linguística, 1*, 53-106.

Langlois, A., Baken, R. J., & Wilder, D. N. (1980). Prespeech respiratory behaviour during the first year of life. In T. Murray & J. Murrary (Eds.), *Infant communication: Cry and early speech*. Houston: College Hill Press.

Lasky, R. E., Syrdal-Lasky, A., & Klein, R. E. (1975). VOT discrimination by four- to six-and-a-half-month-old infants from Spanish environments. *Journal of Experimental Child Psychology, 20*(2), 215-225.

Lasky, R. E., & Williams, A. L. (2005). The development of the auditory system from conception to term. *NeoReviews, 6*(3), e141-e152.

Lecanuet, J.-P. (1998). Foetal responses to auditory and speech stimuli. In A. Slater (Ed.), *Perceptual development: Visual, auditory, and speech perception in infancy* (pp. 317-355). Hove, East Sussex: Psychology Press.

Lederberg, A. R., & Everhart, V. S. (1998). Communication between deaf children and their hearing mothers: The role of language, gesture, and vocalizations. *Journal of Speech, Language and Hearing Research, 41*(4), 887-899.

Levitt, A., & Aydelott Utman, J. (1992). From babbling to the sound systems of English and French: A longitudinal two-case study. *Journal of Child Language, 19*, 19-49.

Levitt, A., & Wang, Q. (1991). Evidence for language-specific rhythmic influences in the reduplicative babbling of French- and English-learning infants. *Language and Speech, 34*(3), 235-249.

Lieberman, P. (1980). On the development of vowel production in young children. In G. H. Yeni-Komshian, J. F. Kavanagh & C. A. Ferguson (Eds.), *Child phonology* (Vol. 1: Production, pp. 113-142). New York: Academic Press.

Lisker, L., & Abramson, A. (1964). A cross-language study of voicing in initial stops: Acoustical measurements. *Word, 20*, 384-422.

Liu, H.-M., Kuhl, P. K., & Tsao, F.-M. (2003). An association between mothers' speech clarity and infants' speech discrimination skills. *Developmental Science 6*(3), F1-F10.

Liu, H.-M., Kuhl, P. K., & Tsao, F.-M. (2007). Acoustic analysis of lexical tone in Mandarin infant-directed speech. *Developmental Psychology, 43*(4), 912-917.

Locke, J. L. (1983). *Phonological acquisition and change*. New York: Academic Press.

Locke, J. L. (1990). Structure and stimulation in the ontogeny of spoken language. *Developmental Psychobiology, 23*(7), 621-643.

Locke, J. L. (1993). *The child's path to spoken language*. Cambridge, MA: Harvard University Press.

Mace, A. L., Wallace, K. L., Whan, M. Q., & Stelmachowicz, P. G. (1991). Relevant factors in the identification of hearing loss. *Ear and Hearing, 12*, 287-293.

MacNeilage, P. F. (1998). The frame/content theory of evolution of speech production. *Behavioral and Brain Sciences, 21*, 499-546.

MacNeilage, P. F., Davis, B. L., Kinney, A., & Matyear, C. L. (2000). The motor core of speech: A comparison of serial organization patterns in infants and languages. *Child Development, 71*(1), 153-163.

Malsheen, B. J. (1980). Two hypotheses for phonetic clarification in the speech of mothers to children. In G. H. Yeni-Komshian, J. F. Kavanagh & C. A. Ferguson (Eds.), *Child Phonology* (Vol. 2. Perception, pp. 173-184). New York: Academic Press.

Mannell, R. (2008). Speech spectra and spectrograms. Retrieved February, 2009 from http://clas.mq.edu.au/speech/acoustics/speech_spectra/vowels.html.

Mannell, R., & Cox, F. (2008). Australian English Monophthongs. Retrieved April, 2009 from http://clas.mq.edu.au/speech/phonetics/phonetics/vowelgraphs/AusE_Monophthongs.html.

Martinez, A. S., Eisenberg, L. S., Boothroyd, A., & Visser-Dumont, L. (2008). Assessing speech pattern contrast perception in infants: Early results on VRASPAC. *Otology and Neurotology, 29*(2), 183-188.

Mattock, K., & Burnham, D. (2006). Chinese and English infants' tone perception: Evidence for perceptual reorganization. *Infancy, 10*(3), 241-264.

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*(4), 465-494.

Maxon, A. B., & Hochberg, I. (1982). Development of psychoacoustic behavior: Sensitivity and discrimination. *Ear and Hearing, 3*, 301-308.

Maye, J., Weiss, D. J., & Aslin, R. N. (2008). Statistical phonetic learning in infants: Facilitation and feature generalizaion. *Developmental Science, 11*(1), 122-134.

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

McGowan, R. S., Nittrouer, S., & Chenausky, K. (2008). Speech production in 12-month-old children with and without hearing loss. *Journal of Speech, Language, and Hearing Research, 51*, 879-888.

Mehl, A. L., & Thomson, V. (2002). The Colorado Newborn Hearing Screening Project, 1992-1999: On the threshold of effective population-based universal newborn hearing screening. *Pediatrics, 109*, e7.

Mehler, J., Dommergues, J. Y., Frauenfelder, U., & Segui, J. (1981). The syllable's role in speech segmentation. *Journal of Verbal Learning and Verbal Behavior, 20*, 298–305.

Mehler, J., Jusczyk, P. W., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition, 29*(2), 143-178.

Miller, G., & Nicely, P. E. (1955). Analysis of perceptual confusions among some English consonants. *Journal of the Acoustical Society of America, 27*, 338-353.

Minagawa-Kawai, Y., Mori, K., Furuya, I., Hayashi, R., & Sato, Y. (2002). Assessing cerebral representations of short and long vowel categories by NIRS. *NeuroReport, 13*, 581-584.

Minagawa-Kawai, Y., Mori, K., Naoi, N., & Kojima, S. (2007). Neural attunement processes in infants during the acquisition of a language-specific phonemic contrast. *The Journal of Neuroscience, 27*(2), 315-321.

Moeller, M. P. (2000). Early intervention and language development in children who are deaf and hard of hearing. *Pediatrics, 106*(3), e43.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., et al. (2007a). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part II - transition to words. *Ear and Hearing, 28*(5), 628-642.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B., et al. (2007b). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I - phonetic development. *Ear and Hearing, 28*(5), 605-627.

Moeller, M. P., Osberger, M. J., & Eccarius, M. (1986). Receptive language skills. In M. J. Osberger (Ed.), *Language and learning skills of hearing-impaired children: ASHA Monographs 23* (pp. 41-53). Rockville, MD: American Speech-Language-Hearing Association.

Molfese, D. L., Freeman, R. B., & Palermo, D. S. (1975). The ontogeny of brain lateralization for speech and nonspeech stimuli. *Brain and Language, 2*(3), 356-368.

Moon, C., Panneton Cooper, R., & Fifer, W. P. (1993). Two-day-olds prefer their native language. *Infant Behavior and Development, 16*(4), 495-500.

Moore, B. C. J. (2001). Dead regions in the cochlear: Diagnosis, perceptual consequences, and implications for the fitting of hearing aids. *Trends in Amplification, 5*, 1-34.

Moore, D. R. (2002). Auditory development and the role of experience. *British Medical Bulletin, 63* 171–181.

Moore, J. K., & Guan, Y. L. (2001). Cytoarchitectural and axonal maturation in human auditory cortex. *Journal of the Association for Research in Otolaryngology, 2*, 297-311.

Morgan, J. L., & Saffran, J. R. (1995). Emerging integration of sequential and suprasegmental information in preverbal speech segmentation. *Child Development, 66*(4), 911-936.

Most, T., Weisel, A., & Lev-Matesky, A. (1996). Speech intelligibility and the evaluation of personal qualities by experienced and inexperienced listeners. *Volta Review, 98*(4), 181-191.

Nakazima, S. (1962). A comparative study of the speech development of Japanese and American English in childhood. *Studia Phonologica, 2*, 27-39.

Nathani, S., Oller, D. K., & Neal, A. R. (2007). On the robustness of vocal development: An examination of infants with moderate-to-severe hearing loss and additional risk factors. *Journal of Speech, Language, and Hearing Research, 50*, 1425-1444.

Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: Toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human Perception and Performance, 24*(3), 756-766.

Nazzi, T., Jusczyk, P. W., & Johnson, E. K. (2000). Language discrimination by English-learning 5-month-olds. *Journal of Memory and Language, 43*, 1-19.

Nelson, H. D., Bougatsos, C., & Nygren, P. (2008). Universal newborn hearing screening: Systematic review to update the 2001 US Preventive Services Task Force recommendation. *Pediatrics, 122*(1), e266-e276.

Netsell, R. (1981). The acquisition of speech motor control: A perspective with directions for research. In R. E. Stark (Ed.), *Language behavior in infancy and early childhood*. New York: Elsevier/North-Holland.

Nittrouer, S. (2001). Challenging the notion of innate phonetic boundaries. *Journal of the Acoustical Society of America, 110*(3), 1598-1605.

Nittrouer, S., Studdert-Kennedy, M., & McGowan, R. S. (1989). The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults. *Journal of Speech and Hearing Research, 32*, 120-132.

Nozza, R. J., & Wilson, W. R. (1984). Masked and unmasked pure-tone thresholds of infants and adults. *Journal of Speech and Hearing Research, 27*, 613-622.

Oller, D. K. (1980). The emergence of the sounds of speech in infancy. In G. H. Yeni-Komshian, J. F. Kavanagh & C. A. Ferguson (Eds.), *Child phonology* (Vol. 1: Production, pp. 93-112). New York: Academic Press.

Oller, D. K. (2000). *The emergence of the speech capacity*. Mahwah, NJ: Lawrence Erlbaum Associates.

Oller, D. K. (2006). Vocal language development in deaf infants: New challenges. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children*. New York: Oxford University Press.

Oller, D. K., & Eilers, R. E. (1982). Similarity of babbling in Spanish- and English-learning babies. *Journal of Child Language, 9*(3), 565-577.

Oller, D. K., & Eilers, R. E. (1988). The role of audition in infant babbling. *Child Development, 59*, 441-449.

Oller, D. K., Eilers, R. E., Urbano, R., & Cobo-Lewis, A. B. (1997). Development of precursors to speech in infants exposed to two languages. *Journal of Child Language, 24*(2), 407-425.

Oller, D. K., Levine, S. L., Cobo-Lewis, A. B., Eilers, R. E., & Pearson, B. Z. (1998). Vocal precursors to linguistic communication: How babbling is connected to meaningful speech. In R. Paul (Ed.), *Exploring the speech-language connection* (pp. 1-23). Baltimore: Paul H. Brookes.

Olney, R. L., & Scholnick, E. K. (1976). Adult judgments of age and linguistic differences in infant vocalization. *Journal of Child Language, 3*(2), 145-155.

Olsho, L. W. (1984). Infant frequency discrimination. *Infant Behavior and Development, 7*, 27-35.

Olsho, L. W. (1985). Infant auditory perception: Tonal masking. *Infant Behavior and Development, 8*(4), 371-384.

Olsho, L. W., Koch, E. G., Carter, E. A., Halpin, C. F., & Spetner, N. B. (1988). Pure-tone sensitivity of human infants. *Journal of the Acoustical Society of America, 84*, 1316-1324.

Olsho, L. W., Koch, E. G., & Halpin, C. F. (1987). Level and age effects in infant frequency discrimination. *Journal of the Acoustical Society of America, 82*, 454-464.

Panneton Cooper, R., Abraham, J., Berman, S., & Staska, M. (1997). The development of infants' preference for motherese. *Infant Behavior and Development, 20*(4), 477-488.

Panneton Cooper, R., & Aslin, R. N. (1990). Preference for infant-directed speech in the first month after birth. *Child Development, 61*, 1584-1595.

Panneton, R., Kitamura, C., Mattock, K., & Burnham, D. (2006). Slow speech enhances younger, but not older infants' perception of vocal emotion. *Research in Human Development, 3*, 7-19.

Paradise, J. L. (1999). Universal newborn hearing screening: Should we leap before we look? *Pediatrics, 103*, 670-672.

Pegg, J. E., & Werker, J. F. (1997). Adult and infant perception of two English phones. *Journal of the Acoustical Society of America, 102*(6), 3742-3753.

Peterson, G. E., & Barney, H. L. (1952). Control methods used in a study of the vowels. *Journal of the Acoustical Society of America, 24*(2), 175-184.

Pienkowski, M., & Harrison, R. V. (2005). Tone frequency maps and receptive fields in the developing chinchilla auditory cortex. *Journal of Neurophysiology, 93*, 454-466.

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*(1), 577-592.

Polka, L., & Bohn, O.-S. (2003). Asymmetries in vowel perception. *Speech Communication, 4*, 221-231.

Polka, L., Colantonio, C., & Sundara, M. (2001). A cross-language comparison of /d/–/ð/ perception: Evidence for a new developmental pattern. *Journal of the Acoustical Society of America, 109*(5), 2190-2201.

Polka, L., & Rvachew, S. (2005). The impact of otitis media with effusion on infant phonetic perception. *Infancy, 8*(2), 101-117.

Polka, L., Rvachew, S., & Mattock, K. (2007). Experiential influences on speech perception and speech production in infancy. In E. Hoff & M. Shatz (Eds.), *Blackwell handbook of language development*. Oxford, England: Blackwell.

Polka, L., Sundara, M., & Blue, S. (2002). The role of language experience in word segmentation: A comparison of English, French, and bilingual infants. *Journal of the Acoustical Society of America, 111*(5), 2455.

Polka, L., & Werker, J. F. (1994). Developmental changes in perception of nonnative vowel contrasts. *Journal of Experimental Psychology, 20*(2), 421-435.

Polonenko, M., Scollie, S. D., Glista, D., Bagatto, M. P., Seewald, R. C., Kertoy, M., et al. (2007, December). *Evaluation of frequency compression: Effects on speech production in children*. Paper presented at the Fourth International Pediatric Conference: A Sound Foundation through Early Amplification, Chicago.

Ponton, C. W., Moore, J. K., & Eggermont, J. J. (1996). Auditory brain stem response generation by parallel pathways: Differential maturation of axonal conduction time and synaptic transmission. *Ear and Hearing, 17*(5), 402-410.

Pujol, R., Lavigne-Rebillard, M., & Uziel, A. (1991). Development of the human cochlea. *Acta Otolaryngolica, 482*, 7-12.

Punch, R., Creed, P. A., & Hyde, M. (2005). Predicting career development in hard-of-hearing adolescents in Australia. *Journal of Deaf Studies and Deaf Education, 10*(2), 146-160.

Querleu, D., Renard, X., Versyp, F., Paris-Delrue, L., & Crepin, G. (1988). Fetal hearing. *European Journal of Obstetrics and Gynecology and Reproductive Biology, 28*(3), 191-212.

Ramsay, D. S. (1984). Onset of duplicated syllable babbling and unimanual handedness in infancy: Evidence for developmental change in hemispheric specialization? *Developmental Psychology, 20*(1), 64-71.

Richard, J. F., Normandeau, J., Brun, V. R., & Maillet, M. (2004). Attracting and maintaining infant attention during habituation: Further evidence of the importance of stimulus complexity. *Infant and Child Development, 13*, 277-286.

Richards, D. S., Frentzen, B., Gerhardt, K. J., McMann, M. E., & Abrams, R. M. (1992). Sound levels in the human uterus. *Obstetrics and Gynecology, 80*, 186-190.

Rivera-Gaxiola, M., Klarman, L., Adrian, G.-S., & Kuhl, P. K. (2005a). Neural patterns to speech and vocabulary growth in American infants. *NeuroReport, 16*(5), 495-498.

Rivera-Gaxiola, M., Silva-Pereyra, J., & Kuhl, P. K. (2005b). Brain potentials to native and non-native speech contrasts in 7- and 11-month-old American infants. *Developmental Science, 8*, 162-172.

Robertson, C., Aldridge, S., Jarman, F., Saunders, K., Poulakis, Z., & Oberklaid, F. (1995). Late diagnosis of congenital sensorineural hearing impairment: Why are detection methods failing? *Archives of Disease in Childhood, 72*, 11-15.

Robinshaw, H. M. (1995). Early intervention for hearing impairment: Differences in the timing of communicative and linguistic development. *British Journal of Audiology, 29*(6), 315-334.

Roizen, N. J. (1999). Etiology of hearing loss in children: Nongenetic causes. *Pediatric Clinics of North America 46*(1), 49-64.

Roug, L., Landberg, I., & Lundberg, L.-J. (1989). Phonetic development in early infancy: A study of four Swedish children during the first eighteen months of life. *Journal of Child Language, 16*, 19-40.

Rubel, E. W. (1984). Ontogeny of auditory system function. *Annual Review of Physiology, 46*, 213-229.

Ruth, R. A., Horner, J. S., McCoy, G. S., & Chandler, C. R. (1983). Comparison of auditory brainstem response and behavioral audiometry in infants. *Scandinavian Audiology, 17*, 94-98.

Rvachew, S., Alhaidarya, A., Mattock, K., & Polka, L. (2008). Emergence of the corner vowels in the babble produced by infants exposed to Canadian English or Canadian French. *Journal of Phonetics, 36*(4), 564-577.

Rvachew, S., Mattock, K., Polka, L., & Ménard, L. (2006). Developmental and cross-linguistic variation in the infant vowel space: The case of Canadian English and Canadian French. *Journal of the Acoustical Society of America, 120*, 2250–2259.

Rvachew, S., Slawinski, E. B., Williams, M., & Green, C. L. (1999). The impact of early onset otitis media on babbling and early language development. *Journal of the Acoustical Society of America 105*(1), 467-475.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science, 274*(5294), 1926-1928.

Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition, 70*(1), 27-52.

Saffran, J. R., Werker, J. F., & Werner, L. A. (2006). The infant's auditory world: Hearing, speech, and the beginnings of language. In D. Kuhn & R. Siegler (Eds.), *Handbook of child psychology* (6th ed., Vol. 2: Cognition, perception, and language., pp. 58-108). New York: Wiley.

Sansavini, A., Bertoncini, J., & Giovanelli, G. (1997). Newborns discriminate the rhythm of multisyllabic stressed words. *Developmental Psychology, 33*(1), 3-11.

Schauwers, K., Gillis, S., Daemers, K., De Beukelaer, C., & Govaerts, P. J. (2004). Cochlear implantation between 5 and 20 months of age: The onset of babbling and the audiologic outcome. *Otology and Neurotology 25*(3), 263-270.

Scheffler, K., Bilecen, D., Schmid, N., Tschopp, K., & Seelig, J. (1998). Auditory cortical responses in hearing subjects and unilateral deaf patients as detected by functional magnetic resonance imaging. *Cerebral Cortex, 8*, 156-163.

Schneider, B., Trehub, S. E., Morrongiello, B. A., & Thorpe, L. A. (1986). Auditory sensitivity in preschool children. *Journal of the Acoustical Society of America, 79*(2), 447-452.

Scollie, S. D. (2006). Fitting hearing aids to babies: Three things you should know [Electronic Version]. *Audiology Online*. Retrieved June 6, 2006, from http://www.audiologyonline.com.

Scollie, S. D., Parsa, V., Glista, D., Bagatto, M. P., Wirtzfeld, M., & Seewald, R. C. (under review). Evaluation of nonlinear frequency compression I: Fitting rationale. *Ear and Hearing*.

Scollie, S. D., Seewald, R. C., Cornelisse, L. E., Moodie, S., Bagatto, M., Laurnagaray, D., et al. (2005). The Desired Sensation Level Multistage Input/Output algorithm. *Trends in Amplification, 9*(4), 159-197.

Seewald, R. C., Moodie, K. S., Scollie, S. D., & Bagatto, M. P. (2005). The DSL method for pediatric hearing instrument fitting: Historical perspective and current issues. *Trends in Amplification, 9*(4), 145-157.

Seewald, R. C., Ross, M., & Spiro, M. K. (1985). Selecting amplification characteristics for young hearing-impaired children. *Ear and Hearing, 6*(1), 48-53.

Seewald, R. C., & Scollie, S. D. (1999). Infants are not average adults: Implications for audiometric testing. *The Hearing Journal, 52*(10), 64-72.

Shahidullah, S., & Hepper, P. G. (1994). Frequency discrimination by the fetus. *Early Human Development, 36*(1), 13-26.

Sharma, A., Dorman, M., & Spahr, A. J. (2002). Rapid development of cortical auditory evoked potentials after early cochlear implantation. *NeuroReport, 13*(10), 1365-1368.

Sharma, A., Martin, K., Roland, P., Bauer, P., Sweeney, M., Gilley, P., et al. (2005). P1 latency is a biomarker for central auditory development in children with hearing impairment. *Journal of the American Academy of Audiology, 16*, 564-573.

Shepherd, R. K., & Hardie, N. A. (2001). Deafness-induced changes in the auditory pathway: Implications for cochlear implants. *Audiology and Neuro-otology, 6*(6), 305-318.

Shi, R., & Werker, J. F. (2001). Six-month-old infants' preference for lexical over grammatical words. *Psychological Science, 12*(1), 70-75.

Shukla, M., Nespor, M., & Mehler, J. (2007). An interaction between prosody and statistics in the segmentation of fluent speech. *Cognitive Psychology, 54*(1), 1-32.

Singh, L., Morgan, J. L., & Best, C. T. (2002). Infants' listening preferences: Baby talk or happy talk? *Infancy, 3*(3), 365-394.

Sininger, Y. S., & Abdala, C. (1996). Hearing threshold as measured by auditory brain stem response in human neonates. *Ear and Hearing, 17*(5), 395-401.

Sinnott, J. M., & Aslin, R. N. (1985). Frequency and intensity discrimination in human infants and adults. *Journal of the Acoustical Society of America, 78*(6), 1986-1992.

Sinnott, J. M., Pisoni, D. B., & Aslin, R. N. (1983). A comparison of pure tone auditory thresholds in human infants and adults. *Infant Behavior and Development, 6*, 3-17.

Snow, C. E., & Ferguson, C. A. (1977). *Talking to children: Language input and acquisition*. Cambridge, England: Cambridge University Press.

Spetner, N. B., & Olsho, L. W. (1990). Auditory frequency resolution in human infancy. *Child Development, 61*(3), 632-652.

Stark, R. E. (1980). Stages of speech development in the first year of life. In G. H. Yeni-Komshian, J. F. Kavanagh & C. A. Ferguson (Eds.), *Child phonology* (Vol. 1: Production, pp. 73-92). New York: Academic Press.

Stelmachowicz, P. G. (2000). Amplification for infants. *Seminars in Hearing, 21*(4), 409-422.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2001). Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults. *Journal of the Acoustical Society of America, 110*(4), 2183-2190.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., Lewis, D. E., & Moeller, M. P. (2004). The importance of high-frequency audibility in the speech and language development of children with hearing loss. *Archives of Otolaryngology - Head and Neck Surgery, 130*, 556-562.

Stern, D., Spieker, S., Barnett, R. K., & MacKain, K. (1983). The prosody of maternal speech: Infant age and context related changes. *Journal of Child Language, 10*(1), 1-15.

Stoel-Gammon, C., & Otomo, K. (1986). Babbling development of hearing-impaired and normally hearing subjects. *51*, 33-41.

Sundberg, U. (2001). Consonant specification in infant-directed speech: Some preliminary results from a study of voice onset time in speech to one-year-olds. *Lund University Department of Linguistics Working Papers, 49*, 148-151.

Sundberg, U., & Lacerda, F. (1999). Voice onset time in speech to infants and adults. *Phonetica, 56*(3-4), 186-199.

Sussman, H. M. (1984). A neuronal model for syllable representation. *Brain and Language, 22*(1), 167-177.

Sussman, H. M., Duder, C., Dalston, E., & Cacciatore, A. (1999). An acoustic analysis of the development of CV coarticulation: A case study. *Journal of Speech, Language, and Hearing Research, 42*, 1080-1096.

Syka, J. (2002). Plastic changes in the central auditory system after hearing loss, restoration of function, and during learning. *Physiological Reviews, 82*, 601-636.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarakan, S. S., et al. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science, 271*(5245), 81-84.

Tharpe, A. M., & Ashmead, D. H. (2001). A longitudinal investigation of infant auditory sensitivity. *American Journal of Audiology, 10*(2), 104-112.

Thelen, E. (1981). Rhythmical behavior in infancy: An ethological perspective. *Developmental Psychology, 17*(3), 237-257.

Thevenin, D. M., Eilers, R. E., Oller, D. K., & Lavoie, L. (1985). Where's the drift in babbling drift? A cross-linguistic study. *Applied Psycholinguistics, 6*, 3-15.

Thiessen, E. D., Hill, E. A., & Saffran, J. R. (2005). Infant-directed speech facilitates word segmentation. *Infancy, 7*(1), 53-71.

Thiessen, E. D., & Saffran, J. R. (2003). When cues collide: Use of stress and statistical cues to word boundaries by 7- to 9-month-old infants. *Developmental Psychology, 39*(4), 706-716.

Thiessen, E. D., & Saffran, J. R. (2004). Spectral tilt as a cue to word segmentation in infancy and adulthood. *Perception and Psychophysics, 66*(5), 779-791.

Ting, J., Smith, J., & Houston, D. (2006). *Infant fricative discrimination using a novel visual habituation paradigm.* Paper presented at the 15th Biennial International Conference on Infant Studies Kyoto, Japan.

Trainor, L. J., & Desjardins, R. N. (2002). Pitch characteristics of infant-directed speech affect infants' ability to discriminate vowels. *Psychonomic Bulletin and Review, 9*, 335-340.

Trehub, S. E. (1973). Infants' sensitivity to vowel and tonal contrasts. *Developmental Psychology, 9*(1), 91-96.

Trehub, S. E. (1976). The discrimination of foreign speech contrasts by infants and adults. *Child Development, 47*, 466-472.

Trehub, S. E., Endman, M. W., & Thorpe, L. A. (1990). Infants' perception of timbre: Classification of complex tones by spectral structure. *Journal of Experimental Child Psychology, 49*, 300-313.

Trehub, S. E., Schneider, B. A., & Endman, M. W. (1980). Developmental changes in infants' sensitivity to octave-band noises. *Journal of Experimental Child Psychology, 29*, 282-293.

Trehub, S. E., Schneider, B. A., Morrongiello, B. A., & Thorpe, L. A. (1988). Auditory sensitivity in school-age children. *Journal of Experimental Child Psychology, 46*, 273-285.

Tsang, C. D., & Trainor, L. J. (2002). Spectral slope discrimination in infancy: Sensitivity to socially important timbres. *Infant Behavior and Development, 25*, 183-194.

Tsushima, T., Takizawa, O., Sasaki, M., Shiraki, S., Nishi, K., Kohno, M., et al. (1994). *Discrimination of English /r-l/ and /w-y/ by Japanese infants at 6-12 months: Language-specific developmental changes in speech perception abilities.* Paper presented at the Third International Conference on Spoken Language Processing, Yokohama.

Turner, C. W., & Cummings, K. J. (1999). Speech audibility for listeners with high-frequency hearing loss. *American Journal of Audiology, 8*, 47-56.

Uhler, K., Fredrickson, T., Gabbard, S. A., & Yoshinaga-Itano, C. (2007, December). *A tool for assessing infant speech perception: Visual reinforcement infant speech discrimination*. Paper presented at the Fourth International Pediatric Conference: A Sound Foundation through Early Amplification, Chicago.

van der Stelt, J. M., & Koopmans-van Beinum, F. (1986). The onset of babbling related to gross motor development. In B. Lindblom & R. Zetterstrom (Eds.), *Precursors of early speech* (pp. 163-173). New York: Academic Press.

Verhaert, N., Willems, M., Van Kerschaver, E., & Desloovere, C. (2008). Impact of early hearing screening and treatment on language development and education level: Evaluation of 6 years of universal newborn hearing screening (ALGOW) in Flanders, Belgium. *International Journal of Pediatric Otorhinolaryngology, 72*, 599-608.

Vihman, M. M. (1996). *Phonological development: The origins of language in the child*. Cambridge, MA: Blackwell.

von Hapsburg, D., & Davis, B. L. (2006). Auditory sensitivity and the prelinguistic vocalizations of early-amplified infants. *Journal of Speech, Language, and Hearing Research, 49*, 809-822.

Vorperian, H. K., Kent, R. D., Lindstrom, M. J., Kalina, C. M., Gentry, L. R., & Yandell, B. S. (2005). Development of vocal tract length during childhood: A magnetic resonance imaging study. *Journal of the Acoustical Society of America, 117*(1), 338-350.

Vouloumanos, A., & Werker, J. F. (2007). Listening to language at birth: Evidence for a bias for speech in neonates. *Developmental Science, 10*(2), 159-164.

Wake, M., Poulakis, Z., Hughes, E. K., Carey-Sargeant, C., & Rickards, F. W. (2005). Hearing impairment: A population study of age at diagnosis, severity, and language outcomes at 7-8 years. *Archives of Disease in Childhood, 90*, 238-244.

Weir, C. (1976). Auditory frequency sensitivity in the neonate: A signal detection analysis. *Journal of Experimental Child Psychology, 21*, 219-225.

Weir, C. (1979). Auditory frequency sensitivity of human newborns: Some data with improved acoustic and behavioral controls. *Perception and Psychophysics, 26*, 287-294.

Werker, J. F., & Curtin, S. (2005). PRIMIR: A developmental model of speech processing. *Language Learning and Development, 1*(2), 197-234.

Werker, J. F., Gilbert, J. H., Humphrey, K., & Tees, R. C. (1981). Developmental aspects of cross-language speech perception. *Child Development, 52*(1), 349-355.

Werker, J. F., & McLeod, P. J. (1989). Infant preference for both male and female infant-directed talk: A developmental study of attentional and affective responsiveness. *Canadian Journal of Psychology, 43*(2), 230-246.

Werker, J. F., Pegg, J. E., & McLeod, P. J. (1994). A cross-language investigation of infant preference for infant-directed communication. *Infant Behavior and Development, 17*, 323-333.

Werker, J. F., Polka, L., & Pegg, J. E. (1997). The conditioned head turn procedure as a method for testing infant speech perception. *Early Development and Parenting, 6*, 171-178.

Werker, J. F., Pons, F., Dietrich, C., Kajikawa, S., Fais, L., & Amano, S. (2007). Infant-directed speech supports phonetic category learning in English and Japanese. *Cognition, 103*, 147-162.

Werker, J. F., Shi, R., Desjardins, R., Pegg, J. E., Polka, L., & Patterson, M. (1998). Three methods for testing infant speech perception. In A. Slater (Ed.), *Perceptual development: Visual, auditory, and speech perception in infancy* (pp. 389-420). East Sussex, UK: Psychology Press.

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

Werner, L. A. (2007). Issues in human auditory development. *Journal of Communication Disorders, 40*, 275-283.

Werner, L. A., Folsom, R. C., & Mancl, L. R. (1993). The relationship between auditory brainstem response and behavioral thresholds in normal hearing infants and adults. *Hearing Research, 68*, 131-141.

Werner, L. A., Folsom, R. C., & Mancl, L. R. (1994). The relationship between auditory brainstem response latencies and behavioral thresholds in normal hearing infants and adults. *Hearing Research, 77*, 88-98.

Werner, L. A., & Gillenwater, J. M. (1990). Pure-tone sensitivity of 2- to 5-week-old infants. *Infant Behavior and Development, 13*(3), 355-375.

Whalen, D., Levitt, A., & Goldstein, L. (2007). VOT in the babbling of French- and English-learning infants. *Journal of Phonetics, 35*, 341–352.

Whalen, D., Levitt, A., & Wang, Q. (1991). Intonational differences between the reduplicative babbling of French- and English-learning infants. *Journal of Child Language, 18*, 501-516.

Wilde, L. (1993). Inferring articulatory movements from acoustic properties at fricative vowel boundaries. *Journal of the Acoustical Society of America, 94*, 1881.

Xu, N., Burnham, D., & Kitamura, C. (2007, August). *Vowels and tones in infant directed speech: Hyperarticulation for both, but different developmental patterns.* Paper presented at the 8th Annual Conference of the International Speech Communication Association, Antwerp, Belgium.

Yoshinaga-Itano, C. (2004). Levels of evidence: Universal newborn hearing screening (UNHS) and early hearing detection and intervention systems (EHDI). *Journal of Communication Disorders, 37*, 451-465.

Yoshinaga-Itano, C. (2007a, November). *The lasting impact of early identification with early intervention services for children who are deaf or hard of hearing*. Paper presented at the HCSNet Workshop on Hearing Prostheses, Sydney.

Yoshinaga-Itano, C. (2007b, March). *Making the most of early identification, making the most from early intervention: Perspective from the USA*. Paper presented at the 20th Annual Workshop on Hearing Screening, London.

Yoshinaga-Itano, C. (2009, March). *Prelinguistic speech discrimination for infants and toddlers with hearing loss*. Paper presented at the MARCS Research Colloquium, Sydney.

Yoshinaga-Itano, C., Coulter, D., & Thomson, V. (2000). The Colorado Newborn Hearing Screening Project: Effects on speech and language development for children with hearing loss. *Journal of Perinatology, 20*(8s), S131-S136.

Yoshinaga-Itano, C., Coulter, D., & Thomson, V. (2001). Developmental outcomes of children born in Colorado hospitals with universal newborn hearing screening programs. *Seminars in Neonatology, 6*(6), 521-529.

Yoshinaga-Itano, C., Sedey, A. L., Coulter, D., & Mehl, A. L. (1998). Language of early- and later-identified children with hearing loss. *Pediatrics, 102*(5), 1161-1171.

Young, A., & Andrews, E. (2001). Parents' experience of universal neonatal hearing screening: A critical review of the literature and its implications for the implementation of new UNHS programs. *Journal of Deaf Studies and Deaf Education, 6*, 149-160.

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.

APPENDICES

APPENDIX A

Advertisement placed in *Sydney's Child*

APPENDIX B

Participant Information and Consent forms

University of Western Sydney

Locked Bag 1797
PENRITH SOUTH DC 1797 Australia

MARCS Auditory Laboratories, University of Western Sydney, Bankstown, Bldg 1

DISCRIMINATING SPECTRAL TILT IN SPEECH: INFANTS

ETHICS APPROVAL NUMBER: 06/050

PARTICIPANT INFORMATION

THIS PROJECT IS BEING CONDUCTED AS PART OF AN ARC (Australian Research Council) GRANT

We thank you for traveling to MARCS Auditory Laboratories at the University of Western Sydney, Bankstown. We invite you and your child to participate in a research study on the perception of speech sounds. We would like permission to enrol your child as a participant. The purpose of this study is to investigate whether infants can tell the difference between different ways frequencies in speech can be presented (as you would find in hearing aids). Benefits of the research include increasing our understanding of speech processing in normal-hearing infants, and will provide valuable information that will assist in the development of hearing aids for infants.

The study will involve your child sitting on your lap and watching a video screen and listening to speech sounds. Speech sounds will be played through speakers and these will change across the course of the session. We will also be recording your infant's heart rate as this provides another measure of the infant's attention when listening to the different sounds. This involves sticking electrodes on your infant's chest and hip region to monitor their heartbeat, a procedure that is completely harmless and painless. A staff member will monitor the session on a television monitor that is connected to a video camera focused on your child. We will videotape the session for later verification of your child's behavioral responses to the sounds. The study will be of brief duration (around 10 minutes) and it will be concluded if your child becomes fussy, or if you wish to finish. During testing, you will be asked to listen to music or speech through headphones, so that you will not influence your child's responses.

All data will be treated in strictest confidence, and only used for scientific purposes. The results will be averaged across all participants and will remain anonymous.

You have a right not to participate in, or subsequently withdraw from the study. Any decision not to participate will not affect any current or future relationship to the University of Western Sydney, or receipt of the advertised benefits.

If you agree to take part in this study, you will be asked to sign a consent form.

If you would like additional information on the project or have any questions please do not hesitate to contact the project supervisor Dr. Christine Kitamura on 9772 6556. Thank you.

NOTE: This study has been approved by the University of Western Sydney Human Research Ethics Committee. The Approval Number is HREC 06/050. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Research Ethics Officers (tel: 02 4736 0883 or 4736 0884). Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

University of Western Sydney

Locked Bag 1797
PENRITH SOUTH DC 1797 Australia

DISCRIMINATING SPECTRAL TILT IN SPEECH: INFANTS

ETHICS APPROVAL NUMBER: 06/050

MARCS Auditory Laboratories
University of Western Sydney, Bankstown Campus
Ph: (02) 9772 6582
Fax: (02) 9772 6326

Project Supervisor: Dr. Christine Kitamura

CONSENT FORM FOR PARTICIPANTS

Please read the information sheet and instructions before signing this.

1. I,..

   of (address) ....

   ....,

   agree to participate as a participant in the experiment described in the participant information statement attached to this form.
2. I acknowledge that I have read the participant information statement, which explains why I have been selected, the aims of the experiment and the nature of the investigation, and the statement has been explained to me to my satisfaction.
3. I understand that I can withdraw from the recording at any time, and I understand that my decision whether or not to participate in or subsequently withdraw from this study will not affect any current or future relationship to the University of Western Sydney, or the receipt of any advertised benefits.
4. I agree that research data gathered from the results of the study may be published or provided to other researchers, provided that I cannot be identified.
5. I understand that if I have any questions relating to my participation in this research, I may contact Dr. Christine Kitamura (tel: 9772 6556) who will be happy to answer them.
6. I acknowledge receipt of a copy of this Consent Form and the Participant Information Statement.
7. I understand the purpose of the study and what is being asked of me, and that I can stop participating at any time without loss of any of the advertised rewards. With this understanding, I agree to take part in this research.

……………………….	………………………………….	Date…………………
Signature of parent/guardian	Please PRINT name	

APPENDIX C

Family Information Sheet

MARCS BABY LAB ***Family Information Sheet***

(All information is strictly confidential. Questions marked with an asterisk* are optional)

Infant's date of birth: ____________________ Mother's Age:__________ Father's Age:__________

*Mother's Occupation: ____________________ *Father's Occupation: ______________________

*Mother's Education: High School TAFE University Masters Ph.D. Other _________________

*Father's Education: High School TAFE University Masters Ph.D. Other _________________

1. Were there any complications of Pregnancy ____
   and/or Labour/Delivery ____
   Have you ever been diagnosed with PND Yes No

2. Was your infant: Fullterm 38-42 wks ☐ Premature ≤ 37 wks ☐……....weeks Post-mature >42 wks ☐

3. Infant's Birthweight: _________ kg 4. *What was your infant's Apgar score? ___________

5. Was your infant's hearing tested at birth? Yes ☐ No ☐ If yes, what was the outcome? ________
   If no, do you have any concerns? ____________

6. Has your infant ever had an ear infection? Yes ☐ No ☐ If yes, how many? _________________

7. Has your infant had any medical/other problems? Yes ☐ No ☐ Please describe: _____________

____

8. Has there been any type of hearing impairment, or deafness in your child's family history? Y ☐ N ☐
   Type/degree ______________________________ Who ___________________________

9. Have there been any types of reading, speech, and/or language problems in the family? Y ☐ N ☐
   Type/degree ______________________________ Who ________________________________

10. What is the primary language spoken in your home? ______________________________________
    Mother's first language ________________________ Father's first language _______________

11. Please list any other languages that are spoken in your home: ______________________________

When was your infant's most recent ear infection? Circle where appropriate.

1st Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

2nd Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

3rd Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

4th Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

5th Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

6th Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

7th Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

8th Visit: This week or 1 2 3 4 5 6 7 8 or 8+ weeks ago

12. How is your baby's health today? 1st Visit:________________________ [Today's Date: __/__/__]

2nd Visit:________________________ [Today's Date: __/__/__]

3rd Visit:________________________ [Today's Date: __/__/__]

4th Visit:________________________ [Today's Date: __/__/__]

5th Visit:________________________ [Today's Date: __/__/__]

6th Visit:________________________ [Today's Date: __/__/__]

7th Visit:________________________ [Today's Date: __/__/__]

8th Visit:________________________ [Today's Date: __/__/__]

We appreciate your participation and thank you for your time today. If you would like to contribute further to the ***MARCS Baby Science Program*** by donating back your $30 travel money please tick the box:

1st Visit: Yes☐

2nd Visit: Yes☐

3rd Visit: Yes☐

4th Visit: Yes☐

5th Visit: Yes☐

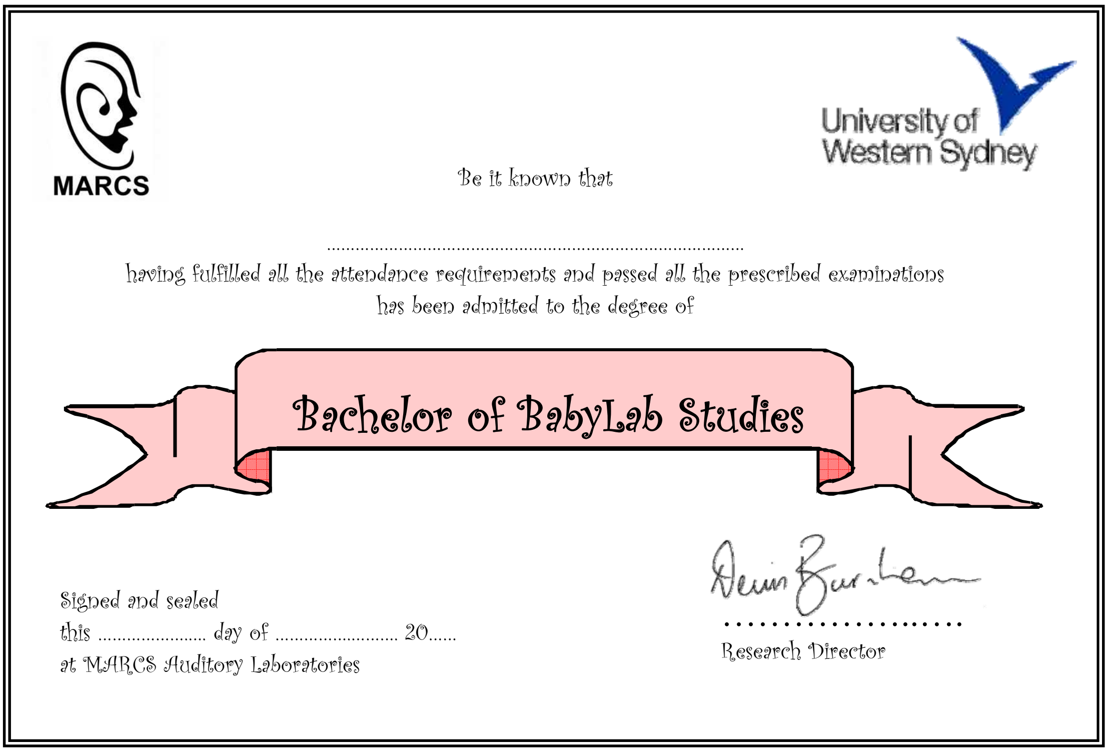
6th Visit: Yes☐

7th Visit: Yes☐

8th Visit: Yes☐

APPENDIX D

Sample BabyLab Certificate



MARCS

University of Western Sydney

Be it known that

....

having fulfilled all the attendance requirements and passed all the prescribed examinations
has been admitted to the degree of

Bachelor of BabyLab Studies

Signed and sealed
this .... day of .... 20......
at MARCS Auditory Laboratories

....
Research Director

APPENDIX E

Fricatives: Analysis of Acoustic Features

Token	Duration (msec)			Pitch Measures (Hz)			Centre of gravity (kHz)	F2 at vowel onset (Hz)
	C	V	Total	Min	Max	F0		
fɐː1	187	626	813	127	186	153	6.06	1325
fɐː2	231	595	825	124	203	162	6.42	1238
fɐː3	251	580	831	148	215	164	5.93	1274
fɐː4	260	575	836	137	211	165	5.85	1287
Means	232	594	826	134	204	161	6.06	1281
sɐː1	268	589	857	126	197	152	8.13	1292
sɐː2	268	602	870	130	216	160	8.16	1356
sɐː3	243	609	852	144	209	164	8.16	1347
sɐː4	237	577	814	137	216	163	8.16	1307
Means	254	594	848	134	210	160	8.15	1325

APPENDIX F

Fricatives: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Normal Speech Condition	6-month-olds	1	4957.0	7716.0	7110.0	0.480
		2	6234.0	3540.0	11166.0	0.759
		3	3760.5	5483.0	4501.5	0.451
		4	6434.0	4782.0	8071.5	0.628
		5	7045.0	7020.5	23549.0	0.770
		6	4261.0	4496.5	7626.0	0.629
		7	5888.5	7385.5	13489.5	0.646
		8	7100.0	13624.5	9503.5	0.411
		9	4131.0	6889.5	15487.5	0.692
		10	6289.0	5653.0	9158.0	0.618
		11	6775.0	7581.0	10114.5	0.572
		12	6244.0	17304.5	27715.0	0.616
		13	4932.0	3830.5	14831.0	0.795
		14	6093.5	7360.5	18306.0	0.713
		15	5267.5	4081.0	12894.0	0.760
		16	3990.5	5478.0	9959.5	0.645
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	5888.5	5182.5	7170.5	0.580
		2	5222.5	7841.0	14280.5	0.646
		3	3615.0	3830.5	4672.0	0.549
		4	4832.0	5042.0	11566.5	0.696
		5	8101.5	2393.5	1967.5	0.451
		6	9188.5	15262.0	4141.0	0.213
		7	9008.0	10299.5	14050.5	0.577
		8	3590.5	1867.5	8087.0	0.812
		9	2989.0	2749.0	8076.5	0.746
		10	2383.5	2128.0	2989.0	0.584
		11	9909.0	6439.0	7496.0	0.538
		12	1842.5	2714.0	2543.5	0.484
		13	5102.5	5603.0	8387.0	0.599
		14	5222.5	595.5	8312.0	0.933
		15	3790.5	12197.5	16528.5	0.575
		16	7385.5	3685.5	17024.5	0.822

Fricatives: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Negative Tilt Condition	6-month-olds	1	8412.5	16634.0	20499.5	0.552
		2	4977.0	6414.0	3495.0	0.353
		3	6344.0	5733.0	7621.0	0.571
		4	6765.0	5588.0	7540.5	0.574
		5	4211.0	4131.0	11676.5	0.739
		6	5898.5	4005.5	5963.5	0.598
		7	8918.0	8302.0	9113.0	0.523
		8	5973.5	8021.5	14060.0	0.637
		9	1187.0	4015.5	9739.0	0.708
		10	8477.0	7185.0	16979.5	0.703
		11	4561.5	6745.0	8116.5	0.546
		12	2488.5	3490.0	2834.0	0.448
		13	9523.5	6609.5	5017.0	0.432
		14	6139.0	4887.0	6299.0	0.563
		15	5503.0	5248.0	2568.5	0.329
		16	3585.5	3365.0	4166.0	0.553
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	446.0	811.0	4892.0	0.858
		2	4701.5	4241.0	4571.5	0.519
		3	6970.0	6644.5	9188.5	0.580
		4	3500.0	5367.5	6078.5	0.531
		5	4691.5	5027.0	5057.0	0.501
		6	6679.5	5142.5	3700.0	0.418
		7	1572.0	2884.0	7596.0	0.725
		8	2749.0	4942.0	18706.5	0.791
		9	4576.5	5367.5	9739.0	0.645
		10	3815.5	3565.0	3004.5	0.457
		11	2609.0	1802.5	1066.5	0.372
		12	4526.5	3890.5	3935.5	0.503
		13	3259.5	2699.0	2999.5	0.526
		14	4801.5	5993.5	3865.5	0.392
		15	4511.5	2899.5	4071.0	0.584
		16	5868.5	7165.0	5287.5	0.476

Fricatives: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Positive Tilt Condition	6-month-olds	1	3665.5	2053.0	2323.5	0.531
		2	4576.5	4086.0	8307.0	0.670
		3	3996.0	4426.5	13244.0	0.749
		4	8617.0	5818.0	13069.0	0.692
		5	12362.5	6980.0	23549.0	0.771
		6	6053.5	5132.5	4552.0	0.470
		7	6804.5	6079.0	15848.0	0.723
		8	3370.0	5478.0	12758.5	0.700
		9	5087.5	3310.0	8843.0	0.728
		10	5883.5	10014.5	20339.0	0.670
		11	5773.0	3615.5	11696.5	0.764
		12	10234.5	9328.5	15477.0	0.624
		13	255.5	3089.5	9749.0	0.759
		14	3505.0	5843.5	12067.5	0.674
		15	1702.5	2674.0	14931.5	0.848
		16	6880.0	3014.0	4656.5	0.607
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	3705.0	7225.5	9058.0	0.556
		2	5127.5	6359.0	8467.0	0.571
		3	7395.5	14411.0	7986.5	0.357
		4	6624.5	7936.5	8026.5	0.503
		5	5763.5	4702.0	3084.5	0.396
		6	7536.0	6715.0	7190.5	0.517
		7	2894.0	3685.5	14295.5	0.795
		8	6574.5	10059.5	5252.5	0.343
		9	3915.5	10049.5	9504.0	0.486
		10	7370.5	17125.0	20614.5	0.546
		11	4496.5	4626.5	17259.5	0.789
		12	10145.0	17590.5	11581.5	0.397
		13	5157.5	5367.5	3054.5	0.363
		14	1987.5	2303.5	7686.0	0.769
		15	11361.0	12097.5	11631.5	0.490
		16	3600.0	4762.0	24189.5	0.836

APPENDIX G

Fricatives: Summaries of ANOVAs

Fixation Durations: Normal Speech Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	5587.81	1123.162	16
	9	5504.81	2531.088	16
	Total	5546.31	1926.669	32
Control	6	7014.38	3645.763	16
	9	5489.63	4078.768	16
	Total	6252.00	3883.455	32
Test	6	12717.88	6177.763	16
	9	8581.06	4871.781	16
	Total	10649.47	5862.376	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	29333331.837	1	29333331.837	3.354	.077	.101
Error	262368606.549	30	8745620.218			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	489364586.312	2	244682293.156	20.815	.000	.410
Trial Type * Age	67559758.271	2	33779879.135	2.874	.064	.087
Error (Trial Type)	705316849.417	60	11755280.824			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	15935835.1	1	15935835.1	1.29	.265	.041
	Con vs. Test	618807405.0	1	618807405.0	22.28	.000	.426
Trial Type * Age	Hab vs. Con	16629144.5	1	16629144.5	1.35	.255	.043
	Con vs. Test	54582964.0	1	54582964.0	1.97	.171	.061
Error (Trial Type)	Hab vs. Con	370814750.4	30	12360491.7			
	Con vs. Test	833237865.9	30	27774595.5			

Fricatives

Fixation Durations: Negative Tilt Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	5810.50	2322.814	16
	9	4080.19	1727.015	16
	Total	4945.34	2196.937	32
Control	6	6273.50	3167.224	16
	9	4277.88	1754.024	16
	Total	5275.69	2714.827	32
Test	6	8480.75	5132.785	16
	9	5860.22	4104.078	16
	Total	7170.48	4761.308	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	35802369.418	1	35802369.418	5.652	.024	.159
Error	190028800.109	30	6334293.337			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	92273418.58	2	46136709.289	6.920	.002	.187
Trial Type * Age	3342367.91	2	1671183.956	.251	.779	.008
Error (Trial Type)	400037002.34	60	6667283.372			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	3492063.8	1	3492063.8	.860	.361	.028
	Con vs. Test	114888166.3	1	114888166.3	8.186	.008	.214
Trial Type * Age	Hab vs. Con	563125.8	1	563125.8	.139	.712	.005
	Con vs. Test	3124062.6	1	3124062.6	.223	.640	.007
Error (Trial Type)	Hab vs. Con	121832181.4	30	4061072.7			
	Con vs. Test	421062686.4	30	14035422. 9			

Fricatives

Fixation Durations: Positive Tilt Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	5548.22	3059.635	16
	9	5853.69	2548.010	16
	Total	5700.95	2774.029	32
Control	6	5059.09	2282.815	16
	9	8438.81	4720.034	16
	Total	6748.95	4031.047	32
Test	6	11963.28	5618.104	16
	9	10555.50	5936.801	16
	Total	11259.39	5730.466	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	4610292.6	1	4610292.647	.474	.497	.016
Error	291896435.5	30	9729881.184			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	558278164.1	2	279139082.0	21.566	.000	.418
Trial Type * Age	94150386.3	2	47075193.167	3.637	.032	.108
Error (Trial Type)	776596534.4	60	12943275.574			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	35145728.0	1	35145728.0	4.060	.053	.119
	Con vs. Test	651009486.1	1	651009486.1	19.124	.000	.389
Trial Type * Age	Hab vs. Con	75608104.5	1	75608104.5	8.735	.006	.226
	Con vs. Test	183361250.0	1	183361250.0	5.386	.027	.152
Error (Trial Type)	Hab vs. Con	259677088.0	30	8655902.9			
	Con vs. Test	1021231376.4	30	34041045.9			

Fricatives

Discrimination Indices: All Conditions

BOTH AGE GROUPS

Between-Subjects Factors

		N
Age	6	48
	9	48
Tilt	-1	32
	0	32
	1	32

Descriptive Statistics

Age	Tilt	Mean	Std. Deviation	N
6	-1	.5513	.11815	16
	0	.6369	.11435	16
	1	.6856	.09458	16
	Total	.6246	.12097	48
9	-1	.5506	.14121	16
	0	.6131	.16938	16
	1	.5462	.16828	16
	Total	.5700	.15972	48
Total	-1	.5509	.12807	32
	0	.6250	.14267	32
	1	.6159	.15180	32
	Total	.5973	.14357	96

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Age	.072	1	.072	3.799	.054
Linear Trend	.068	1	.068	3.592	.061
Quadratic Trend	.037	1	.037	1.958	.165
Age * Linear	.077	1	.077	4.091	.046
Age * Quadratic	.011	1	.011	0.606	.438
Error	1.824	90	.020		
Total	32.101	96			

Fricatives

Discrimination Indices: All Conditions

6-MONTH-OLDS

Between-Subjects Factors

		N
Tilt	-1	16
	0	16
	1	16

Descriptive Statistics

Tilt	Mean	Std. Deviation	N
-1	.5513	.11815	16
0	.6369	.11435	16
1	.6856	.09458	16
Total	.6246	.12097	48

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Linear Trend	.144	1	.144	12.044	.001
Quadratic Trend	.004	1	.004	.302	.585
Error	.540	45	.012		

9-MONTH-OLDS

Between-Subjects Factors

		N
Tilt	-1	16
	0	16
	1	16

Descriptive Statistics

Tilt	Mean	Std. Deviation	N
-1	.5506	.14121	16
0	.6131	.16938	16
1	.5462	.16828	16
Total	.5700	.15972	48

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Linear Trend	.000	1	.000	.006	.939
Quadratic Trend	.045	1	.045	1.740	.194
Error	1.154	45	.026		

APPENDIX H

Approximants: Analysis of Acoustic Features

Token	Duration (msec)			F0 at vowel midpoint (Hz)	F3 at onset (Hz)	F3 at vowel midpoint (Hz)
	C	V	Total			
li:1	144	539	682	150	2926	3185
li:2	144	536	681	150	2923	3187
li:3	153	530	683	150	3091	3195
li:4	124	507	630	151	3078	3234
Means	141	528	669	150	3005	3200
ri:1	111	568	679	146	2059	3104
ri:2	86	574	660	147	2005	3167
ri:3	106	513	619	150	2029	3201
ri:4	83	539	622	153	2131	3186
Means	96	549	645	149	2071	3164

APPENDIX I

Approximants: Raw Data

Condition	Group	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Normal Speech Condition	6-month-olds	1	2733.5	3515.0	3770.5	0.518
		2	5047.5	3770.0	3455.0	0.478
		3	3840.5	5202.5	10705.5	0.673
		4	3995.5	2629.0	2518.5	0.489
		5	4386.5	3910.5	5673.5	0.592
		6	4772.0	2118.0	5292.5	0.714
		7	2653.5	4922.0	2954.5	0.375
		8	4246.0	4697.0	9518.5	0.670
		9	3159.5	2954.0	15928.0	0.844
		10	3535.0	3420.0	2714.0	0.442
		11	9849.5	14781.0	12117.5	0.450
		12	3485.0	3330.0	2899.5	0.465
		13	3930.5	3590.0	5668.0	0.612
		14	4591.5	2634.0	3330.0	0.558
		15	4291.5	3575.0	8632.0	0.707
		16	3149.5	2773.5	6960.0	0.715
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	2078.0	6749.5	10175.0	0.601
		2	3194.5	3099.5	5778.5	0.651
		3	4226.0	5833.5	3665.0	0.386
		4	3159.5	2814.0	15101.5	0.843
		5	4016.0	2799.0	16143.0	0.852
		6	5167.5	6104.0	5407.5	0.470
		7	4481.5	6153.5	5377.5	0.466
		8	4301.5	4501.5	7846.5	0.635
		9	4611.5	4071.0	8337.0	0.672
		10	4376.5	3780.5	8948.0	0.703
		11	4005.5	3205.0	2544.0	0.443
		12	3931.0	3980.5	3685.5	0.481
		13	5553.0	5783.5	5538.0	0.489
		14	4546.5	8522.5	12237.5	0.589
		15	6759.5	4807.0	13660.0	0.740
		16	5883.5	11046.0	4471.5	0.288

Approximants: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Negative Tilt Condition	6-month-olds	1	4842.0	5247.5	7771.5	0.596
		2	3335.0	3069.5	6770.0	0.688
		3	3089.5	4576.5	2669.0	0.368
		4	2328.5	3845.5	3875.5	0.501
		5	4221.0	3745.5	3911.0	0.510
		6	3690.0	3289.5	2474.0	0.429
		7	6284.0	3270.0	8256.5	0.716
		8	2533.5	4942.0	4181.0	0.458
		9	4211.0	2974.5	4050.5	0.576
		10	7115.5	5858.5	2418.5	0.292
		11	8963.0	9338.5	10855.5	0.537
		12	2283.0	9513.5	12122.5	0.560
		13	4021.0	2178.0	3505.0	0.616
		14	1507.0	1342.0	3109.5	0.698
		15	6178.5	7906.5	5698.0	0.418
		16	3945.5	4171.0	4241.0	0.504
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	771.0	1192.0	1452.0	0.549
		2	5868.5	4351.5	7596.0	0.636
		3	2373.5	2689.0	1652.5	0.381
		4	3565.0	3265.0	6464.0	0.664
		5	2303.5	3069.5	1928.0	0.386
		6	3359.5	4771.5	3459.5	0.420
		7	6474.5	2864.0	13870.0	0.829
		8	5508.0	3830.5	4166.0	0.521
		9	2323.5	2929.5	3230.0	0.524
		10	6970.0	4116.0	2213.5	0.350
		11	3029.5	1321.5	9944.5	0.883
		12	1472.0	2113.0	1357.0	0.391
		13	6108.5	4071.0	4351.5	0.517
		14	8412.0	4181.0	7020.0	0.627
		15	5988.5	10445.5	7481.0	0.417
		16	2709.0	3024.0	5162.5	0.631

Approximants: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Positive Tilt Condition	6-month-olds	1	4932.0	5272.5	9468.5	0.642
		2	2694.0	4436.0	4742.0	0.517
		3	1277.0	1627.5	1272.0	0.439
		4	3555.0	4101.0	5508.0	0.573
		5	5398.0	5037.0	27665.0	0.846
		6	9653.5	5783.5	8242.0	0.588
		7	5883.5	5242.5	7961.5	0.603
		8	2578.5	5222.5	18236.5	0.777
		9	7701.0	13980.0	20204.0	0.591
		10	9068.0	13209.0	14571.0	0.525
		11	3785.5	5853.5	4977.0	0.460
		12	4626.5	5112.0	11081.0	0.684
		13	10315.0	3329.5	4296.0	0.563
		14	10225.0	8332.0	10720.0	0.563
		15	6679.5	9218.0	17019.5	0.649
		16	7230.5	7210.0	5983.5	0.454
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	866.0	5733.5	9694.0	0.628
		2	3114.5	4406.5	3029.5	0.407
		3	4341.5	3359.5	7405.5	0.688
		4	1352.0	1282.0	1116.5	0.465
		5	5177.0	6504.5	4056.0	0.384
		6	5653.0	4416.0	4902.0	0.526
		7	5052.5	2408.5	3209.5	0.571
		8	4631.5	3815.5	3680.5	0.491
		9	2163.0	1948.0	2408.5	0.553
		10	1893.0	1637.0	1547.0	0.486
		11	5132.0	5773.0	5247.5	0.476
		12	3685.0	5042.0	3094.5	0.380
		13	4692.0	9158.5	12112.5	0.569
		14	2178.5	1582.5	4577.0	0.743
		15	4056.0	2423.5	1567.0	0.393
		16	1177.0	250.0	4782.0	0.950

APPENDIX J

Approximants: Summaries of ANOVAs

Fixation Durations: Normal Speech Condition

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Between-Subjects Factors

		N
Age	6	16
	9	16

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	4229.19	1654.747	16
	9	4393.22	1116.719	16
	Total	4311.20	1391.147	32
Control	6	4238.84	2937.291	16
	9	5203.16	2241.320	16
	Total	4721.00	2616.370	32
Test	6	6383.59	3975.811	16
	9	8057.25	4294.696	16
	Total	7220.42	4158.867	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	6978848.000	1	6978848.000	1.775	.193	.056
Error	117959400.611	30	3931980.020			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	158705033.849	2	79352516.924	11.217	.000	.272
Trial Type * Age	9126896.734	2	4563448.367	.645	.528	.021
Error (Trial Type)	424440802.417	60	7074013.374			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	5373871.3	1	5373871.3	1.409	.245	.045
	Con vs. Test	199907510.7	1	199907510.7	9.420	.005	.239
Trial Type * Age	Hab vs. Con	5123600.6	1	5123600.6	1.343	.256	.043
	Con vs. Test	4025348.4	1	4025348.4	.190	.666	.006
Error (Trial Type)	Hab vs. Con	114434139.8	30	3814471.3			
	Con vs. Test	636657310.6	30	21221910.3			

Approximants

Fixation Durations: Negative Tilt Condition

Between-Subjects Factors

		N
Age	6.00	16
	9.00	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	4284.25	1988.101	16
	9	4202.28	2255.066	16
	Total	4243.27	2091.626	32
Control	6	4704.28	2393.192	16
	9	3639.66	2088.053	16
	Total	4171.97	2274.525	32
Test	6	5369.31	2984.705	16
	9	5084.25	3493.284	16
	Total	5226.78	3199.408	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	1821901.883	1	1821901.883	.449	.508	.015
Error	121663642.311	30	4055454.744			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	22240166.818	2	11120083.409	2.797	.069	.085
Trial Type * Age	4305541.516	2	2152770.758	.541	.585	.018
Error (Trial Type)	238559609.833	60	3975993.497			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	162663.8	1	162663.8	.033	.858	.001
	Con vs. Test	35604141.1	1	35604141.1	3.715	.063	.110
Trial Type * Age	Hab vs. Con	7724906.4	1	7724906.4	1.555	.222	.049
	Con vs. Test	4861741.5	1	4861741.5	.507	.482	.017
Error (Trial Type)	Hab vs. Con	149078022.0	30	4969267.4			
	Con vs. Test	287550278.3	30	9585009.3			

Approximants

Fixation Durations: Positive Tilt Condition

Between-Subjects Factors

		N
Age	6.00	16
	9.00	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	5975.16	2867.264	16
	9	3447.78	1621.596	16
	Total	4711.47	2626.556	32
Control	6	6435.41	3323.343	16
	9	3733.78	2336.273	16
	Total	5084.59	3141.460	32
Test	6	10746.72	7082.261	16
	9	4526.84	2988.657	16
	Total	7636.78	6210.948	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	116512656.681	1	116512656.681	14.936	.001	.332
Error	234028808.677	30	7800960.289			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	162243589.583	2	81121794.792	8.186	.001	.214
Trial Type * Age	69448006.333	2	34724003.167	3.504	.036	.105
Error (Trial Type)	594574333.250	60	9909572.221			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	4455112.5	1	4455112.5	.653	.426	.021
	Con vs. Test	208437153.1	1	208437153.1	9.812	.004	.246
Trial Type * Age	Hab vs. Con	242904.5	1	242904.5	.036	.852	.001
	Con vs. Test	99024664.5	1	99024664.5	4.662	.039	.134
Error (Trial Type)	Hab vs. Con	204766785.5	30	6825559.5			
	Con vs. Test	637292029.9	30	21243067.7			

Approximants

Discrimination Indices: All Conditions

BOTH AGE GROUPS

Between-Subjects Factors

		N
Age	6	48
	9	48
Tilt	-1	32
	0	32
	1	32

Descriptive Statistics

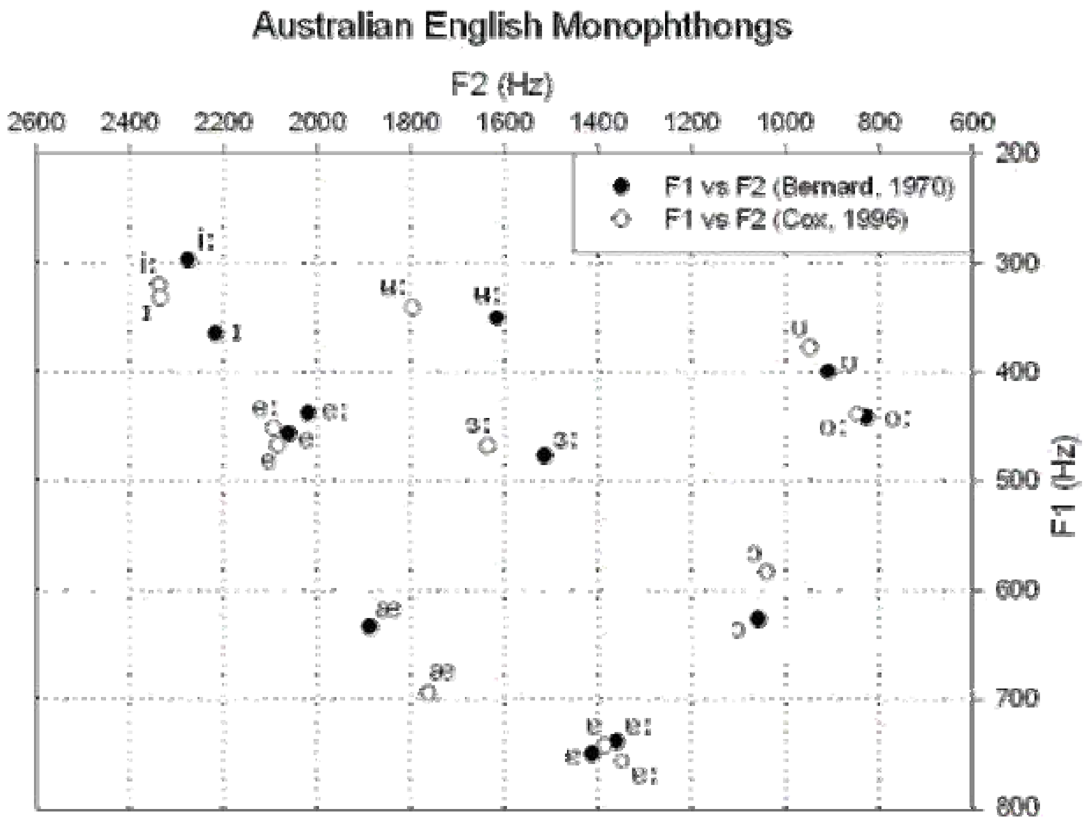
Age	Tilt	Mean	Std. Deviation	N
6	-1	.5297	.11983	16
	0	.5815	.12999	16
	1	.5920	.11128	16
	Total	.5677	.12119	48
9	-1	.5453	.15895	16
	0	.5818	.16038	16
	1	.5445	.15171	16
	Total	.5572	.15469	48
Total	-1	.5375	.13870	32
	0	.5817	.14361	32
	1	.5683	.13308	32
	Total	.5625	.13832	96

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Age	.003	1	.003	0.135	.714
Linear Trend	.015	1	.015	0.773	.382
Quadratic Trend	.018	1	.018	0.900	.345
Age * Linear	.016	1	.016	0.814	.369
Age * Quadratic	.001	1	.001	0.072	.789
Error	1.765	90	.020		
Total	32.190	96			

APPENDIX K

Australian English Vowel Chart



This vowel chart shows the monophthongs of Australian English. It is a summary of the results of Bernard (1970) and Cox (1996), and includes male speakers only. Female speakers show a similar pattern. Reprinted from Mannell and Cox (2008) with permission.

APPENDIX L

Vowels: Analysis of Acoustic Features

Token	Duration (msec)			Frequency measures at vowel midpoint (Hz)			
	V	C	Total	F0	F1	F2	F3
ɐt1	246	318	564	170	904	1402	2945
ɐt2	210	299	509	172	883	1357	2879
ɐt3	196	308	504	174	875	1378	2942
ɐt4	219	316	535	170	914	1371	2938
Means	218	310	528	172	894	1377	2926
ɔt1	200	331	531	186	711	1062	2888
ɔt2	222	334	556	176	706	1076	2848
ɔt3	230	269	499	165	749	1089	2912
ɔt4	294	283	577	172	743	1060	2907
Means	237	304	541	175	728	1072	2889

APPENDIX M

Vowels: Raw Data

Condition	Age group	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Normal Speech Condition	6-month-olds	1	2834.0	5252.5	14085.5	0.728
		2	3505.0	5868.0	5933.5	0.503
		3	2423.5	1552.5	2889.5	0.650
		4	1437.0	1572.0	20759.5	0.930
		5	1787.5	2368.5	4076.0	0.632
		6	4576.5	3339.5	3460.0	0.509
		7	2854.0	2323.0	16984.5	0.880
		8	2779.0	2764.0	8382.0	0.752
		9	3265.0	3249.5	5988.5	0.648
		10	3465.0	6464.5	3370.0	0.343
		11	7476.0	13359.0	9909.5	0.426
		12	3224.5	7085.5	10189.5	0.590
		13	3089.0	3049.5	4101.0	0.574
		14	3074.5	5483.0	7591.0	0.581
		15	3640.5	4576.5	9148.0	0.667
		16	2673.5	1857.5	1467.0	0.441
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	2944.0	2353.5	2063.0	0.467
		2	2764.0	5373.0	7305.5	0.576
		3	2258.0	3375.0	5468.0	0.618
		4	2659.0	2378.5	7991.5	0.771
		5	4030.5	3319.5	2103.0	0.388
		6	2548.5	2043.0	4101.0	0.667
		7	3380.0	2884.0	4041.0	0.584
		8	3840.5	2708.5	6139.0	0.694
		9	3400.0	6664.5	6945.0	0.510
		10	4431.5	1602.0	5348.0	0.769
		11	7295.5	3885.5	9618.5	0.712
		12	2784.0	3129.5	2929.0	0.483
		13	2809.0	3280.0	3094.0	0.485
		14	3404.5	11311.5	16554.0	0.594
		15	2634.0	3194.5	8978.0	0.738
		16	2428.5	2203.5	5678.0	0.720

Vowels: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Negative Tilt Condition	6-month-olds	1	2113.0	2854.0	3159.5	0.525
		2	1707.0	2353.0	5348.0	0.694
		3	5563.0	7821.5	6559.5	0.456
		4	1122.0	2093.0	4461.5	0.681
		5	8447.0	4110.5	5713.5	0.582
		6	5503.0	4356.5	11226.5	0.720
		7	4436.5	1898.0	9268.0	0.830
		8	8116.5	8863.0	3976.0	0.310
		9	5863.5	9033.0	4186.0	0.317
		10	4781.5	8167.0	7386.0	0.475
		11	4296.0	4076.0	7225.5	0.639
		12	2614.0	4727.0	9423.5	0.666
		13	5668.0	4627.0	8262.0	0.641
		14	6138.5	4166.0	5943.5	0.588
		15	8397.5	6344.0	11396.5	0.642
		16	4426.5	4601.5	19397.5	0.808
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		.0	4977.0	6104.0	3525.0	0.366
		2	5718.0	4541.5	5077.5	0.528
		3	1913.0	986.5	966.5	0.495
		4	5087.5	4646.5	2454.0	0.346
		5	4051.0	4131.0	4952.0	0.545
		6	4526.5	4511.5	2994.0	0.399
		7	6104.0	3860.5	3740.0	0.492
		8	2884.5	3340.0	3600.0	0.519
		9	6659.5	3760.0	6394.5	0.630
		10	3975.5	3760.5	5478.0	0.593
		11	5277.5	3951.0	3119.5	0.441
		12	4196.0	3024.5	12853.5	0.810
		13	6053.5	4721.5	15101.5	0.762
		14	1672.5	3009.0	3109.5	0.508
		15	5277.5	6554.5	4176.0	0.389
		16	5643.0	3670.0	4116.0	0.529

Vowels: Raw Data

Condition	Age	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
Positive Tilt Condition	6-month-olds	1	3425.0	6725.0	4301.0	0.390
		2	3425.0	2398.5	2153.0	0.473
		3	7150.0	5933.5	6779.5	0.533
		4	2979.0	5823.0	5668.5	0.493
		5	2658.5	1687.0	2283.5	0.575
		6	7441.0	3580.5	4421.5	0.552
		7	1727.5	5167.0	5933.5	0.535
		8	4566.5	1692.5	5348.0	0.760
		9	2969.5	2759.0	10270.0	0.788
		10	1522.0	2674.0	771.0	0.224
		11	11051.0	5262.5	12483.0	0.703
		12	7095.5	5833.5	8387.0	0.590
		13	6524.5	9864.0	4771.5	0.326
		14	2984.5	5543.0	25642.0	0.822
		15	2909.5	1927.5	3094.5	0.616
		16	8262.0	5062.0	7731.0	0.604
	9-month-olds	ID	Habituation Trials (msec)	Control Trials (msec)	Test Trials (msec)	Disc Index
		1	4496.5	9553.5	9508.5	0.499
		2	2569.0	6850.0	6855.0	0.500
		3	1141.5	2679.0	6504.5	0.708
		4	5878.5	9083.0	10675.5	0.540
		5	3074.5	2684.0	2979.5	0.526
		6	5968.5	816.0	3960.5	0.829
		7	5603.0	4862.0	4286.5	0.469
		8	7731.0	4887.0	3560.0	0.421
		9	8347.0	3475.0	6719.5	0.659
		10	4066.0	5122.5	6008.5	0.540
		11	4141.0	5312.5	3685.5	0.410
		12	5417.5	5563.0	4827.0	0.465
		13	3415.0	2208.0	6930.0	0.758
		14	10460.0	5222.5	1927.5	0.270
		15	2964.5	4506.5	2133.0	0.321
		16	5598.5	6810.0	4967.0	0.422

APPENDIX N

Vowels: Summaries of ANOVAs

Fixation Durations: Normal Speech Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	3256.53	1339.960	16
	9	3350.72	1217.705	16
	Total	3303.63	1260.382	32
Control	6	4385.31	2986.412	16
	9	3731.63	2382.484	16
	Total	4058.47	2678.118	32
Test	6	8020.94	5418.400	16
	9	6147.28	3618.497	16
	Total	7084.11	4631.148	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	5262443.9	1	5262443.855	1.154	.291	.037
Error	136835183.8	30	4561172.793			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	256174425.474	2	128087212.737	15.545	.000	.341
Trial Type * Age	15786799.443	2	7893399.721	.958	.389	.031
Error (Trial Type)	494380890.917	60	8239681.515			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	18233250.8	1	18233250.8	3.381	.076	.101
	Con vs. Test	292944038.1	1	292944038.1	13.810	.001	.315
Trial Type * Age	Hab vs. Con	4474536.1	1	4474536.1	.830	.370	.027
	Con vs. Test	11906590.0	1	11906590.0	.561	.460	.018
Error (Trial Type)	Hab vs. Con	161798749.1	30	5393291.6			
	Con vs. Test	636372885.6	30	21212429.5			

Vowels

Fixation Durations: Negative Tilt Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	4949.59	2269.435	16
	9	4626.03	1456.803	16
	Total	4787.81	1883.089	32
Control	6	5005.69	2363.564	16
	9	4035.78	1268.556	16
	Total	4520.73	1929.907	32
Test	6	7683.31	4001.504	16
	9	5103.59	3713.010	16
	Total	6393.45	4016.967	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	13334739.0	1	13334739.031	4.199	.049	.123
Error	95265658.3	30	3175521.943			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	65669205.953	2	32834602.977	5.209	.008	.148
Trial Type * Age	21598660.141	2	10799330.070	1.713	.189	.054
Error (Trial Type)	378204455.406	60	6303407.590			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	2282583.2	1	2282583.2	.733	.399	.024
	Con vs. Test	112226416.5	1	112226416.5	5.972	.021	.166
Trial Type * Age	Hab vs. Con	3342081.9	1	3342081.9	1.074	.308	.035
	Con vs. Test	20731970.3	1	20731970.3	1.103	.302	.035
Error (Trial Type)	Hab vs. Con	93372584.1	30	3112419.5			
	Con vs. Test	563782187.7	30	18792739.6			

Vowels

Fixation Durations: Positive Tilt Condition

Between-Subjects Factors

		N
Age	6	16
	9	16

Within-Subjects Factors

Trial Type	Dependent Variable
1	Habituation
2	Control
3	Test

Descriptive Statistics

	Age	Mean	Std. Deviation	N
Habituation	6	4793.19	2756.138	16
	9	5054.50	2367.211	16
	Total	4923.84	2530.753	32
Control	6	4495.78	2247.609	16
	9	4977.16	2355.527	16
	Total	4736.47	2277.928	32
Test	6	6877.41	5858.769	16
	9	5345.50	2465.707	16
	Total	6111.45	4489.584	32

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Age	553658.9	1	553658.876	.116	.736	.004
Error	143649801.6	30	4788326.719			

Tests of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	35585146.130	2	17792573.065	2.006	.143	.063
Trial Type * Age	19512966.349	2	9756483.174	1.100	.339	.035
Error (Trial Type)	532127542.188	60	8868792.370			

Tests of Within-Subjects Contrasts

Source	Trial Type	Type III Sum of Squares	df	Mean Square	F	Sig.	η_p^2
Trial Type	Hab vs. Con	1123500.5	1	1123500.5	.124	.727	.004
	Con vs. Test	60498625.0	1	60498625.0	3.174	.085	.096
Trial Type * Age	Hab vs. Con	387420.0	1	387420.0	.043	.838	.001
	Con vs. Test	32426411.1	1	32426411.1	1.701	.202	.054
Error (Trial Type)	Hab vs. Con	272162606.0	30	9072086.9			
	Con vs. Test	571770159.6	30	19059005.3			

Vowels

Discrimination Indices: All Conditions

Between-Subjects Factors

		N
Age	6	48
	9	48
Tilt	-1	32
	0	32
	1	32

Descriptive Statistics

Age	Tilt	Mean	Std. Deviation	N
6	-1	.5984	.15111	16
	0	.6158	.15780	16
	1	.5616	.16280	16
	Total	.5919	.15561	48
9	-1	.5219	.13013	16
	0	.6111	.11942	16
	1	.5211	.15239	16
	Total	.5514	.13853	48
Total	-1	.5602	.14406	32
	0	.6135	.13767	32
	1	.5413	.15648	32
	Total	.5717	.14795	96

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Age	.040	1	.040	1.843	.178
Linear Trend	.006	1	.006	0.265	.608
Quadratic Trend	.084	1	.084	3.914	.051
Age * Linear	.005	1	.005	0.241	.625
Age * Quadratic	.015	1	.015	0.721	.398
Error	1.930	90	.021		
Total	33.451	96			

APPENDIX O

Presentations during Candidature

Conference Presentations

Beach, E.F. & Kitamura, C., Dillon, H., Ching, T. & Burnham, D. The effect of spectral tilt on infants' discrimination of fricatives. Poster presented at Interspeech Conference, Brisbane, 22-26 September, 2008.

Beach, E.F., Kitamura, C., Dillon, H., Noble, W., Ching, T. High-, low- or no frequency emphasis: Which is best for babies? Poster presented at the Sound Foundation Through Early Amplification Conference, Chicago, 6-8 December, 2007.

Beach, E.F., Kitamura, C., Dillon, H., Noble, W. Tuning hearing aids for infant ears. Paper presented at the Australian Human Development Conference, Sydney, 5-8 July, 2007.

Beach, E.F., Kitamura, C., Dillon, H., Noble, W., Ching, T. The effect of spectral tilt on infants' speech perception: Implications for infant hearing aids. Poster presented at 34th Australasian Experimental Psychology Conference, Canberra, 13-15 April, 2007.

Invited Presentations

Beach, E.F., Kitamura, C., Dillon, H., Noble, W., Ching, T. Exploring the effect of positive, negative and no spectral tilt on infants' discrimination of speech sounds. Paper presented at the HCSNet Priority Area Workshop Bringing Together the Science and Practice of Hearing Prostheses, Sydney, 14 November, 2007.

Beach, E.F., Kitamura, C., Dillon, H., Noble, W. Tuning hearing aids for infant Ears. Paper presented at the MARCS/School of Psychology Expanding Horizons II: Postgraduate Research Conference, 8 August 2007.

Submitted Articles

Kitamura, C., Beach, E. F., Dillon, H., Ching, T., & Burnham, D. (under review). Infant preferences for spectral tilt. *Journal of Speech, Language, and Hearing Research.*

Beach, E.F. & Kitamura, C. (under review). The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: I. High-frequency fricatives. *Journal of Speech, Language, and Hearing Research.*

Beach, E.F. & Kitamura, C. (under review). The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: II. Mid-frequency approximants. *Journal of Speech, Language, and Hearing Research.*

Beach, E.F. & Kitamura, C. (under review). The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: III. Low-frequency vowels. *Journal of Speech, Language, and Hearing Research.*

APPENDIX P

Fricatives manuscript

The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: I. High-frequency fricatives

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Keywords: spectral tilt, infant development, speech perception, hearing aids, fricative discrimination

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Introduction

Because HI infants are now routinely fitted with hearing aids in the first few weeks of life, it is important to understand how best to amplify speech via hearing aids to facilitate the acquisition of speech and language. When normal speech, which has a natural spectral slope of -3 to -5 dB/octave above 800 Hz (Byrne et al., 1994), is amplified through a hearing aid, the natural spectral slope can be maintained, or else it can be 'tilted' to emphasise either the high or low frequencies in the speech spectrum. Presently, amplification schemes designed for children (including infants) attempt to preserve the natural loudness balance between low- and high-frequency regions (Cornelisse, Seewald, & Jamieson, 1995). However, there is no empirical evidence as to whether or not this strategy is best for infants. It may be that infants would benefit from a frequency response that alters the natural balance between low- and high-frequency sounds. If so, two alternatives are possible. Infants may be best served by speech amplified with a positive spectral tilt, which results in emphasis on high-frequency components of the spectrum while low-frequency energy is attenuated. On the other hand, a negative spectral tilt, which boosts low-frequency energy at the expense of high-frequency energy, may be preferable. The challenge for those fitting infants with hearing aids is to provide the optimal spectral tilt and sufficient audibility to allow the process of language acquisition to unfold. As a first step towards determining an optimal spectral tilt for HI infants, this study examines *NH* infants' ability to discriminate high-frequency consonantal information under conditions which simulate high- and low-frequency emphasis. Although NH infants' auditory experience and language development are likely to differ from those of HI infants, it is important to obtain data from NH infants as a reference point against which HI infants' perception can be compared.

In HI adults, providing high-frequency gain is usually of little or no benefit, and, in some cases, may be detrimental to intelligibility, particularly for listeners with steeply sloping high-frequency HL (Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998; Moore, 2001; Turner & Cummings, 1999). On the other hand, children benefit from increased high-frequency bandwidths because children aged from 5 to 10 years, perceive fricative and sibilant sounds better when they have access to high-frequency energy, irrespective of whether they have normal or impaired hearing (Kortekaas & Stelmachowicz, 2000; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). Unfortunately, these findings may not necessarily extend to infants for two reasons. Firstly, infants' basic auditory abilities are not yet fully developed and, as such, their perception of speech and other sounds is demonstrably different from that of older listeners, including children older than 12 months (see Saffran et al., 2006). For example, we know that 6 months after birth, infants' perception of both the frequency and intensity of nonspeech auditory events is still developing (Olsho et al., 1988; Sinnott & Aslin, 1985) with performance at high frequencies reaching maturity earlier than performance at low frequencies (Maxon & Hochberg, 1982). Secondly, infants have not yet acquired language, and are not able to use knowledge of language or contextual cues in the same way that older HI listeners can when communicating with others.

So we are left with a unique problem: how to amplify speech via infants' hearing aids to ensure they have access to the best possible speech signal. Infants with NH acquire language through exposure to a rich and complete source of speech input from their caregivers and others around them and, in an ideal world, infants with HL would also have access to all parts of the speech spectrum. This would give them the best possible chance to develop language in a manner, and at a rate, comparable to that of their NH counterparts. However, the limitations of hearing aid technology and the impact of those deficits commonly associated with HL, such as reduced dynamic range, impaired frequency resolution etc (Dillon, 2001), mean that providing access to all parts of the speech spectrum through hearing aids is not possible. Thus, it is necessary to discover which parts of the speech spectrum are most useful for transmitting essential speech information. That is, it is essential to identify the qualities of the spectrum that should be preserved or enhanced to enable the best outcomes for language development.

Language Development

In their first few months, NH infants use prosodic cues, such as rhythm and intonation, to recognise their native language (Mehler et al., 1988; Moon et al., 1993); to discriminate two non-native languages (Nazzi et al., 2000); and to discriminate words (Karzon, 1985). Similarly, infants under 6 months are attracted to the exaggerated low-frequency prosodic and affective features of IDS (Fernald, 1985; Hayashi et al., 2001; Panneton Cooper & Aslin, 1990). During their second six months of life, infants begin to rely less on prosody and demonstrate a growing awareness of the finer details of their native language. Their preference for the exaggerated prosodic characteristics of IDS starts to wane (Hayashi et al., 2001; Kitamura & Notley, accepted May 2008) and at around 9 months, they are sensitive to their native language's phonetic and phonotactic characteristics (Friederici & Wessels, 1993; Jusczyk et al., 1993b).

A similar developmental shift is also evident in NH infants' perception of the segmental units of speech. In early infancy, the ability to discriminate speech sounds depends on innate psychoacoustic thresholds (Aslin & Pisoni, 1980) and young infants can discriminate non-native (Trehub, 1976) and native (Eimas et al., 1971) speech sounds, with little or no appreciation of the phonological status of what is being heard (e.g., Pegg & Werker, 1997). When infants reach about 6 months, they begin to attune to native vowels, such that good exemplars of native vowels 'attract' poor and non-native exemplars, thus making them difficult to discriminate (Kuhl et al., 1992; Polka & Werker, 1994). Later, at around 9 months, infants' perception of consonants begins to mature and the ability to discriminate non-native consonant contrasts declines (Best & McRoberts, 2003; Werker & Tees, 1984) while discrimination of native consonants improves (Kuhl et al., 2008).

This suggests that there are two relatively distinct phases of infant speech development. The early phase is characterised by attention to the low-frequency prosodic aspects of language, which tend to occur over longer linguistic units, and the formation of native vowel categories (Cutler & Mehler, 1993). As infants accumulate experience with the native language, they shift from the first, relatively nonlinguistic mode of speech perception to a sharper, more detailed, language-specific mode. In this second phase, there is less reliance on prosody, and, in its place, comes a growing awareness of the phonetic/phonotactic rules of the native language. Infants also exhibit more sophisticated perception of speech sounds, ignoring allophonic variation and attuning to native-language consonants (Burnham, Tyler, & Horlyck, 2002).

Spectral Tilt Perception

Developmental differences also occur in 6- and 9-month-old NH infants' perception of spectrally tilted speech, which has been investigated, for the first time, in two recent studies conducted in our laboratory (Kitamura et al., submitted; Kitamura et al., accepted with revisions). Prior to this, spectral tilt discrimination in infancy had been demonstrated only using complex tones (Clarkson, 1996; Tsang & Trainor, 2002). The first study found that, although infants at both ages could discriminate unmodified speech from speech with a low- or high-frequency emphasis when the spectral tilt was set at ±9 dB/octave, when the tilt was reduced to ±6 dB/octave, a developmental pattern emerged. Younger infants were only able to distinguish speech with low-frequency emphasis from unmodified speech, and older infants were only able to discriminate speech with high-frequency emphasis from unmodified speech (Kitamura et al., accepted with revisions). In the second study, which examined infants' attentional preferences for spectral tilt, the younger infants again showed that they were able to differentiate between unmodified speech and speech with a low-frequency emphasis, but not between unmodified speech and speech with a high-frequency emphasis. In contrast, the older infants had no difficulty discriminating speech with high-frequency emphasis from unmodified speech, or speech with low-frequency emphasis from unmodified speech. Furthermore, the older infants demonstrated a distinct preference for speech with a positive tilt over unmodified speech, and unmodified speech over speech with a negative tilt. The younger infants demonstrated the same trend, but their preference for positive tilt over unmodified speech was not statistically significant (Kitamura et al., submitted).

Rationale for this Study

From the results of these studies, we might infer that, at least in terms of sound quality, HI infants might prefer wearing hearing aids that provide high-frequency emphasis. However, this leaves unresolved the question of whether or not high-frequency emphasis improves the intelligibility of speech for infants. Resolving this question is the ultimate goal of this research, and as a first step, this study investigated the ability of 6- and 9-month-old NH infants to discriminate the relatively difficult high-frequency fricative contrast /f/-/s/ under conditions where the speech signal had high- or low-frequency emphasis, or was left unmodified. For adults, fricatives are among the most confusable contrasts in the English repertoire (Miller & Nicely, 1955) and infants, too, who are normally adept at discriminating speech sounds, find fricative contrasts difficult (Eilers et al., 1977; Holmberg et al., 1977; Nittrouer, 2001; Ting et al., 2006). Fricatives are characterised by the high-frequency aperiodic noise that is produced by air being pushed through two closely held articulators and typically, the concentration of energy for both /s/ and /f/ is above 4000 Hz, with higher frequency values obtained for /s/ than /f/ (Clark & Yallop, 1990).

Each of the fricatives was followed by the relatively low-frequency Australian English long vowel /ɐː/ to form a monosyllable, and the natural spectral tilt of the syllables was altered in either a negative or positive direction to create stimuli with either low- or high-frequency emphasis respectively. Because positive spectral tilt increases the intensity of the fricative portion and decreases emphasis on the vowel, one might expect that positive spectral tilt would facilitate the discrimination of fricatives. However, an alternative outcome was also considered. Given that infants in the first six months perceive speech in a more psychoacoustic manner, it was possible that the younger infants would be able to distinguish the two fricatives, regardless of the spectral tilt. For them, the differences between /f/ and /s/ would not be occluded by the modified spectral tilts, and discrimination would be possible in all tilt conditions. On the other hand, the older infants may find that, because they have progressed from a language-general to a language-specific mode of speech perception, the tilting of the speech spectra would alter the stimuli to such an extent that discrimination would not be possible.

Methods

An habituation-dishabituation procedure was used to test 6- and 9-month-old infants' discrimination of /fɐː/ versus /sɐː/. Infants were assigned to one of three conditions: (i) Normal Speech, in which the contrast was presented in an unmodified form; (ii) Negative Tilt, in which the contrast was spectrally tilted at -6 dB/octave; or (iii) Positive Tilt, in which the contrast was spectrally tilted at +6 dB/octave.

Participants

In total, 118 full term infants were tested, but 22 failed to complete the task resulting in a final sample of 96. For full participant details, see Table 1. The infants were recruited through an advertisement placed in *Sydney's Child* magazine and all were from homes in which English was the primary language. After undergoing informed consent procedures in accordance with the policies of the UWS Human Ethics Committee, parents were asked to complete a Family Information Questionnaire and all reported that their infants had passed their newborn hearing screen, had no history of ear infections, and were healthy at the time of testing. Participants received a certificate, small gift and travel stipend.

Condition	Σ	Age (months)		Data not included	
	(n)	M	Range	Failed to habituate	Cried
Normal Speech	16	6.0	5.7 – 6.4	1	2
	16	9.0	8.5 – 9.4	2	-
Negative Tilt	16	6.0	5.6 – 6.4	3	-
	16	8.8	8.6 – 9.2	3	-
Positive Tilt	16	6.1	5.6 – 6.4	4	-
	16	8.9	8.7 – 9.3	6	1

Table 1. Fricatives: Mean age, age range of participants, and rate of task completion for each condition.

Speech stimulus materials

The speech stimuli consisted of four tokens of /fɐː/ and four tokens of /sɐː/ produced by an adult female speaker of Australian English. Four measures were obtained for each token: overall duration, vowel F0, centre of gravity of the fricative, and frequency of the second formant (F2) at vowel onset (Table 2). Duration and F0 were similar for all tokens of /fɐː/ and /sɐː/ but the syllables differed in terms of centre of gravity and frequency of F2 at vowel onset. The difference in centre of gravity for /f/ and /s/ reflects the level of differentiation in the speaker's vocal tract when articulating the two fricatives (Nittrouer et al., 1989), with the centre of gravity expected to be higher for /s/ than for /f/ (Jongman et al., 2000). Similarly, the F2 onset frequency of /s/ is usually higher than /f/ because its place of constriction is further back in the vocal tract (Wilde, 1993).

Stimulus	Duration (msec)	F0 (Hz)	Centre of gravity (kHz)	F2 at vowel onset (Hz)
/fɐː/	826 (10)	161 (5)	6.06 (.25)	1281 (36)
/sɐː/	848 (24)	160 (5)	8.15 (.01)	1325 (31)

Table 2. Mean acoustic measures for /fɐː/ and /sɐː/ averaged across four tokens.
Standard deviations are in parentheses.

Two FFT filters were constructed in Adobe Audition: one with a negative, and one with a positive 6 dB/octave slope. The filters were applied to the fricative tokens over the full bandwidth, with the slope occurring between 250 to 4000 Hz around a fulcrum of 1000 Hz. As shown in Figure 1, the tokens with a negative spectral tilt had increased emphasis on all frequencies below 1000 Hz, and reduced emphasis on all frequencies higher than 1000 Hz. These were used as stimuli for the Negative Tilt condition. The tokens with a positive spectral tilt had increased emphasis on frequencies over 1000 Hz and reduced emphasis on the lower frequencies. These were used as stimuli for the Positive Tilt condition. The original, unmodified speech tokens were used as the stimuli for the Normal Speech condition. The four tokens of each of the fricative stimuli were presented to the infants in a continuous loop with a 600 ms interval between each syllable, and at an average 65dBA SPL.

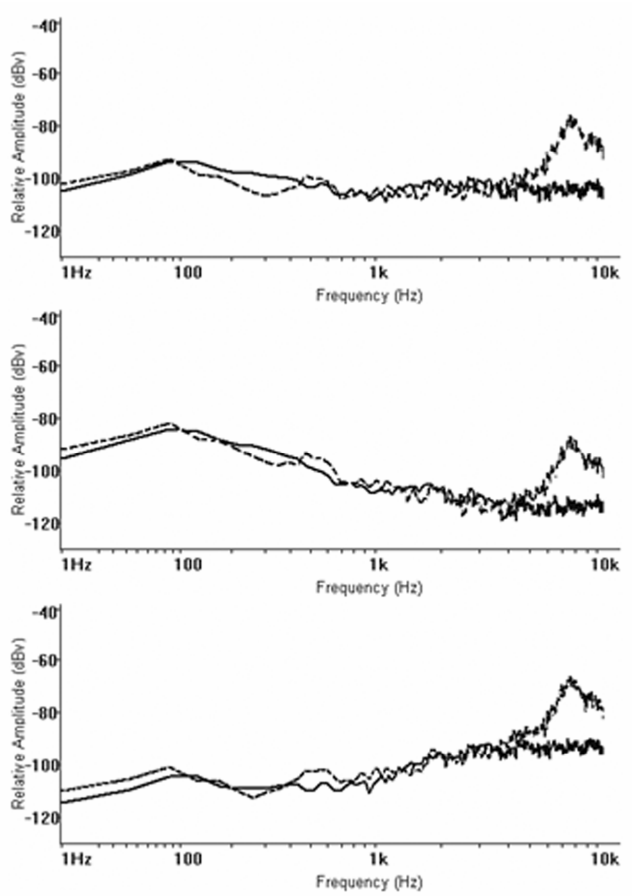

Figure 1. Long-term average speech spectra of fricative portions of single tokens of /fɐː/ and /sɐː/. Dotted line is /s/ and solid line is /f/. The top panel is the Normal Speech condition. The middle panel is the Negative Tilt condition, showing the effect of applying emphasis to frequencies below 1 kHz. The bottom panel is the Positive Tilt condition, showing that emphasis has been applied above 1 kHz.

Materials and Apparatus

Testing was conducted in two adjacent rooms, a sound-attenuated test room, and a control room. Infants were seated on their parent's lap facing a 43 cm LCD television screen which was positioned approximately 1.5 m from the infant, and at an angle of 8° to the right of the infant's sagittal plane. The audio stimuli were presented through an Edirol micromonitor speaker placed to the immediate right of the screen. Two types of visual stimuli were presented on the screen: (i) a multi-coloured bullseye shown in conjunction with the speech stimuli during habituation, control and test trials; and (ii) a silent visual stimulus presented at the beginning of each trial to attract the infant's attention to the screen. The attention-getting stimulus was an arrangement of coloured shapes that loomed continuously from the centre of the screen. A digital video camera was positioned directly opposite the infant at eye level, and connected to (i) a DVD recorder on which each test session was recorded, and (ii) a television monitor in the control room, which the experimenter used to judge the infant's head and eye movements in real time. Parents were instructed not to interact with their babies, but to further minimise any possible parental influence, parents listened to repeated speech syllables (on one channel) overlaid with music (on the second channel) over AKG K270 studio headphones.

Procedure

Each infant was tested individually using an infant-controlled habituation-dishabituation procedure. The habituation stimulus was presented on repeated trials until there was a mean 50% decline in fixation duration on three consecutive trials compared to the mean fixation duration of the first three trials. Thus, each infant was exposed to a minimum of six habituation trials. If the habituation criterion was not met after 30 trials had elapsed, the procedure was discontinued, and no further testing was conducted. Once the habituation criterion was met, two no-change control trials (of the habituation stimulus) were presented to ensure infants had habituated, and did not show spontaneous recovery in fixation duration. Spontaneous recovery was defined as an increase of at least 100% in mean fixation times during control trials compared to the final two habituation trials, and any infants whose fixation times met this criterion were deemed not to have habituated, and their data were excluded from the final analyses. The control trials were followed by two test trials which comprised the new test stimulus alternating with the habituation stimulus, /sɐː/ /fɐː/ /sɐː/ /fɐː/ etc (Best & Jones, 1998; Houston et al., 2007). Infants who showed recovery in fixation duration in test compared to control trials (longer mean fixation) were said to have discriminated the two stimuli. Trials began when the infant fixated the attention-getting stimulus for at least 3 seconds and ended when the infant looked away from the television screen for more than 1.2 sec, or when a total of 30 sec had elapsed. The experimenter recorded the infant's visual fixations to the screen by pressing the space bar on a keyboard when the infant looked at the screen, and releasing the space bar when the infant looked elsewhere. The keystrokes were recorded via purpose-written software which also controlled sequencing of the experiment.

Results

Fixation Durations

Mean fixation durations for (i) the final two habituation trials; (ii) the two no-change control trials; and (iii) the two test trials that presented the novel stimuli were calculated for each infant in each of the three conditions. Means and standard errors for each age group in each of the conditions are shown in Figure 2.

For each condition, a 2 (age) x (3) (trial type) ANOVA was conducted. Two planned contrasts for trial type were included in the analyses. The first contrast was used to confirm that habituation had occurred, i.e., that there was no recovery in fixation duration for control trials compared to habituation trials. The second contrast tested whether there was an increase in fixation duration for test trials compared to control trials, i.e., whether or not the infants discriminated the two stimulus sounds. Where there was a significant interaction and/or a main effect for trial type, simple effects tests were conducted to examine which age group/s discriminated /f/-/s/ in each condition.

For all three conditions, the contrast testing recovery in control trials confirmed there were no significant differences in fixation durations between habituation and control trials, all ps > 0.05. However, a significant age x trial type interaction in the Positive Tilt condition showed that 6-month-old infants' fixation times decreased in control trials compared to habituation trials, whereas the 9-month-old infants' fixation times increased, $F(1,30) = 8.74$, $p = 0.006$, $\eta_p^2 = 0.23$. Next, to determine whether or not infants could discriminate /f/-/s/ in each of the three conditions, the results for the contrast which tested whether infants' fixation durations increased in test trials compared to control trials were examined.

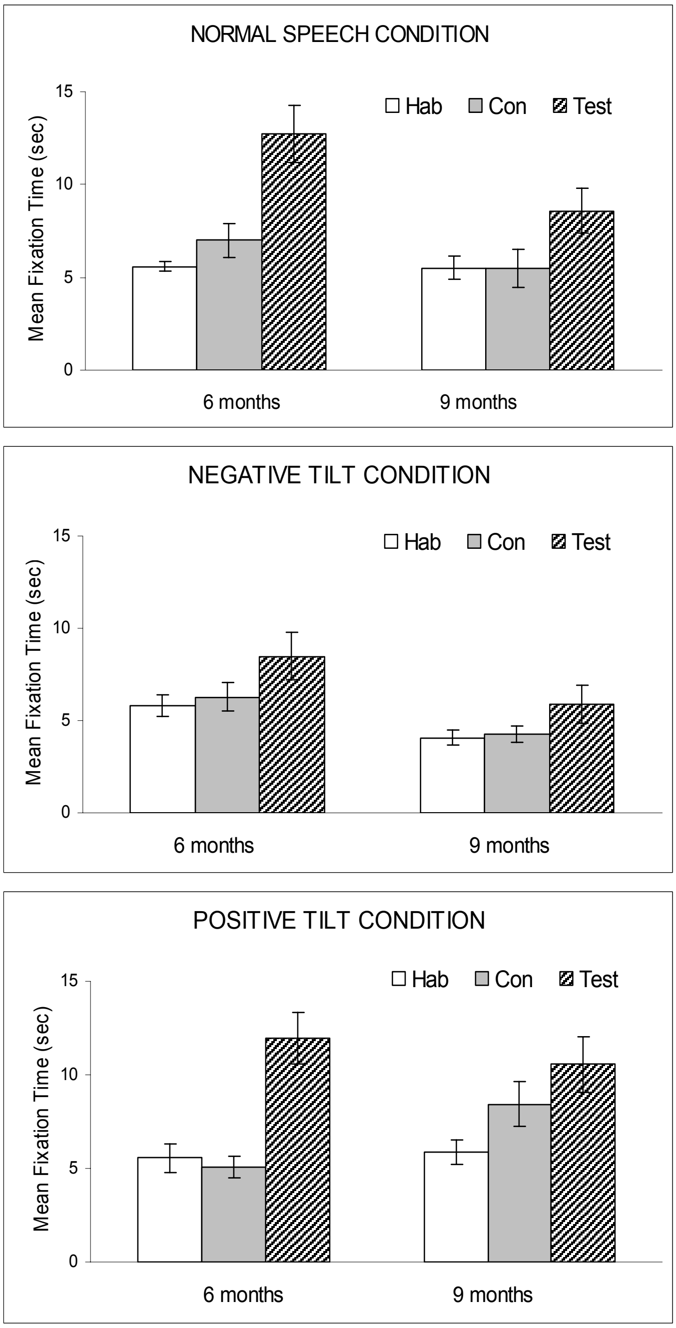

Figure 2. Mean fixation times for 6- and 9-month-old infants.
Top panel: Normal Speech condition, Middle panel: Negative Tilt condition, Bottom panel: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

Normal Speech Condition

The ANOVA results showed a significant main effect for trial type indicating that, averaged across age, infants increased their fixation durations in test trials (M_{test} = 10.6 sec) compared to control trials (M_{con} = 6.3 sec), $F(1,30) = 22.28$, $p < 0.001$, η_p^2

= 0.43. There was no main effect for age, or age x trial type interaction. Simple effects tests confirmed that both 6-month-old, $F(1,30) = 18.30$, $p < 0.001$, and 9-month-old infants, $F(1,30) = 5.64$, $p < 0.03$, fixated longer in the test compared to control trials. Thus when speech was presented with a natural tilt in the Normal Speech condition, both the younger and older age groups could discriminate /f/ versus /s/.

Negative Tilt Condition

The results for this condition also showed a significant main effect for trial type. Irrespective of age, infants increased their fixation durations from control trials (M_{con} = 5.3 sec) to test trials (M_{test} = 7.2 sec), $F(1,30) = 8.19$, $p < 0.01$, $\eta_p^2 = 0.21$. There was also a significant main effect for age, $F(1,30) = 5.65$, $p < 0.02$, $\eta_p^2 = 0.16$, indicating that 6-month-olds' looking times across all trial types (M_{6mo} = 6.9 sec) were longer than those of 9-month-olds (M_{9mo} = 4.7 sec). There was no age x trial type interaction. Simple effects tests revealed that the 6-month-old infants fixated significantly longer during test trials compared to control trials, $F(1,30) = 6.02$, $p < 0.02$, but the result for 9-month-old infants was not significant, $F(1,30) = 2.65$, $p > 0.11$. The results indicate that, although the younger infants were able to discriminate /f/-/s/ successfully in the Negative Tilt condition, the older group found discrimination in this condition more difficult.

Positive Tilt Condition

In the Positive Tilt condition, there was a significant main effect for trial type revealing longer fixation durations for test trials (M_{test} = 11.3 sec) compared to control trials (M_{con} = 6.8 sec), $F(1,30) = 19.12$, $p < 0.001$, $\eta_p^2 = 0.39$. More importantly, there was a significant age x trial type interaction, $F(1,30) = 5.39$, $p < 0.04$, $\eta_p^2 = 0.15$, indicating that 6-month-old infants showed a larger increase in fixation times from control to test trials than 9-month-old infants. The superior performance of the younger group was confirmed by simple effects tests which were significant for 6-month-old infants, $F(1,30) = 40.12$, $p < 0.001$, but not 9-month-old infants, $F(1,30) = 1.46$, $p > 0.23$. The results from the Positive Tilt condition clearly show that the younger infants, but not the older infants, were able to discriminate the fricative contrast when high-frequency emphasis was applied.

Discrimination Indices

The above analyses show that 6-month-old infants can discriminate /f/-/s/ regardless of the tilt condition in which the contrast is presented, but 9-month-old infants can discriminate /f/-/s/ only when it is presented under normal speech conditions. To probe each age group's relative ability to discriminate /f/-/s/ across conditions, a discrimination index (DI) was determined by calculating the amount of time infants spent fixating in test trials as a proportion of the time spent fixating during both control and test trials (DI = test/test+control). Because the DI factors out individual differences in infants' test-phase looking times, it allows for comparisons between infants in different conditions. A DI greater than 0.50 indicates that an infant looked longer during test than control trials and DIs approach 1 as the relative difference between test and control fixations increases. Thus, the DI is a type of novelty preference score and a group of infants with a mean DI significantly above 0.50 indicates that the group discriminated the test and control stimuli (Arterberry & Bornstein, 2002). A DI was calculated for each infant in each age group, and the mean DI for each age group and condition are shown in Figure 3.

Each mean DI was compared to chance performance (0.50) and results of one-tailed t-tests showed that the 6-month-olds' DIs were above chance in all conditions (all *p*s < 0.05). For 9-month-olds, the DI exceeded chance in the Normal Speech condition only $t(1,15) = 2.67$, $p < 0.01$. These results are consistent with the analyses of fixation durations presented earlier. That is, 6-month-olds are capable of discriminating /f/-/s/ regardless of whether spectral tilt is modified or not, whereas 9-month-olds discriminated /f/-/s/ only in the unmodified condition.

Next, the DIs were analysed in a 2 (age) x 3 (condition) ANOVA. Planned contrasts tested for linear and quadratic trends across the three equally spaced conditions: Negative Tilt (tilt factor: -6), Normal Speech (tilt factor: 0) and Positive Tilt (tilt factor: +6) (see Howell, 2007). These contrasts were included to ascertain the pattern of discrimination performance across the three conditions, and specifically, whether performance improved as the tilt factor increased.

The results revealed a significant linear x age interaction, $F(1,90) = 4.09$, $p < 0.05$, $\eta_p^2 = 0.12$. There were no significant main effects for age or condition. As shown in Figure 3, there was an upward linear trend across the three conditions for 6-month-old infants, $DI_{Neg} < DI_{NS} < DI_{Pos}$, but not for 9-month-old infants because their peak performance was in the Normal Speech condition, $DI_{NS} > DI_{Pos} \approx DI_{Neg}$. Separate ANOVAs for each age group confirmed the significant linear trend for 6-month-old infants, $F(1,45) = 12.04$, $p < 0.001$, but not 9-month-olds, $p > 0.9$. Thus, 6-month-old infants' discrimination performance was best in the Positive Tilt condition, whereas the 9-month-old infants' best performance was in the Normal Speech condition.

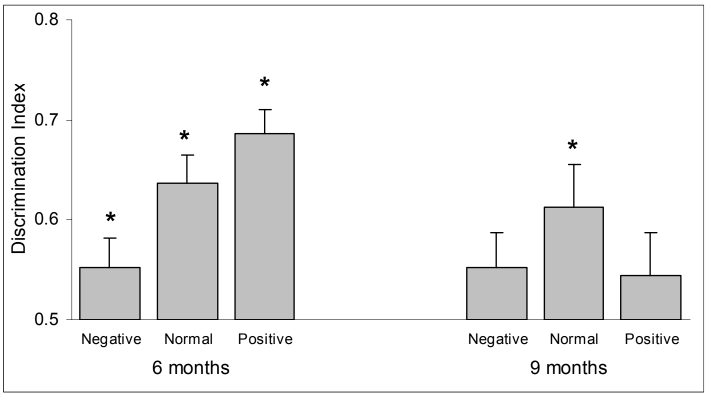

Figure 311 Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
There is a linear improvement across conditions for the 6-month-old infants, but not for the 9-month-old infants. Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

In summary, the results show that 6-month-old infants can discriminate /f/-/s/ irrespective of the condition, but 9-month-old infants can discriminate /f/-/s/ only in the Normal Speech condition. When DIs are used as a measure of discrimination performance, it is clear that 6-month-old infants' performance improves as the direction of tilt changes from negative to positive, but that of 9-month-old infants does not. Thus, although it might have been expected that high-frequency emphasis would facilitate discrimination of high-frequency fricatives, this proved to be the case only for 6-month-old infants; 9-month-old infants performed best in the Normal Speech condition.

Discussion

The results show that both 6- and 9-month-old NH infants can discriminate /f/-/s/. Six-month-old infants discriminated the fricative contrast in all three conditions, with the strongest discrimination performance observed in the Positive Tilt condition, and the weakest performance in the Negative Tilt condition. In contrast, 9-month-old infants successfully discriminated the contrast only in the Normal Speech condition, not the Positive and Negative Tilt conditions. How do these results bear on the hypotheses? First, it was proposed that positive spectral tilt would facilitate the discrimination of fricatives because of the high-frequency emphasis it provides. Although this expectation was met for 6-month-old infants, it was not the case for the older infants, who seemed to find the Positive Tilt just as difficult as the Negative Tilt condition. Second, it was predicted that 6-month-old infants would be able to discriminate /f/-/s/ in all three conditions because of their language-general mode of speech perception, and that 9-month-old infants would discriminate the contrast only in the Normal Speech condition because of their increasingly language-specific speech perception strategies. The results confirm this prediction, with 6-month-old infants able to discriminate /f/-/s/ in all three conditions and 9-month-old infants in the Normal Speech condition only.

One of the most interesting findings of this study is that older infants perform more poorly than their younger counterparts when attempting to discriminate fricatives with modified spectral tilt. There is considerable evidence that infants' general auditory perception abilities, such as intensity perception (Trehub et al., 1988) and frequency discrimination (Aslin, 1989; Olsho, 1984) continue to improve beyond 6 months of age. If both age groups had treated the discrimination task as an auditory exercise, then one would expect the 9-month-olds to outperform the 6-month-olds because of the older infants' superior auditory skills. The poorer performance by 9-month-old infants suggests that, for them, this is no longer simply an auditory discrimination task. Rather, they are bringing to the task a new linguistically driven mode of perception, which is beginning to displace their earlier reliance on acoustic cues. At 9 months of age, perceptual reorganisation is under way – speech sounds are being perceived in terms of how they fit into the infant's native-language categories and hence infants at this age perceive speech in a truly speech-specific mode that was not possible just a few months earlier.

The infant's progression to a language-specific mode at around 9 months is well-documented. In the first six months of life, infants perceive speech in a language-general manner and discriminate native and non-native speech contrasts alike (Eimas et al., 1971; Trehub, 1976). In the second six months, infants' increased experience with the native language sees them shift to a language-specific mode of speech perception, such that they now recognise their native language via its phonetic and phonotactic features (Jusczyk et al., 1993b), and attune to the consonants of the native language (Werker & Tees, 1984). Crucially, the accumulated exposure to the native language is a critical factor that propels infants into the second phase of language development. If HI infants are to progress from the initial acoustic mode to the language-specific mode of speech perception, it is likely that they will need maximal exposure to the native language in the early months. This would then lay the foundation for HI infants to acquire language in a manner, and at a rate, comparable to that of infants with normal hearing.

Although it is acknowledged that tests with HI infants are required before any recommendations can be put forward, the data reported here have some potential implications for HI infants' amplification strategies. Because the results show that 6-, but not 9-month-old NH infants can perceive differences in a relatively difficult fricative contrast with positive and negative spectral tilts, it seems that older infants are less able to cope with modifications to spectral tilt than younger infants. This suggests that amplification in the second half-year of life might need to be precisely specified, and follow as closely as possible the spectral characteristics of normal speech, just as current child/infant amplification strategies aim to do. Although the perceptual adaptability demonstrated by the younger infants implies that it is less crucial that they receive speech with a natural spectral tilt, in fact, it may be equally important for them to be exposed to such speech, especially if young HI infants are to advance towards the second language-specific phase of speech perception. If we assume that the more closely the speech input resembles its natural spectral form, the better it will be for HI listeners, then younger infants may benefit just as much as their older counterparts from amplification which delivers natural and precise spectral characteristics.

Of particular relevance here is a new method of signal processing that aims to preserve the spectral characteristics of high-frequency speech sounds, such as fricatives. Known as nonlinear frequency compression (NFC), this method takes the high-frequency region of the speech spectrum and compresses it by a pre-determined ratio, leaving the lower frequencies intact (Scollie et al., under review). This technology shows promise in terms of providing listeners with greater access to high-frequency information and, in turn, improving listeners' production of high-frequency consonants (Polonenko et al., 2007). One of the advantages of NFC is that, although the shape of the spectrum may be somewhat compromised, its natural tilt is maintained. As the results show that older infants struggle to discriminate high-frequency sounds with altered tilt, a method such as NFC, which does not involve spectral tilting, may be particularly useful for ensuring the intelligibility of high-frequency sounds for infants.

As stated earlier, before any firm recommendations can be made in respect to the best amplification method for infants' hearing aids, further work is needed. First, testing HI infants' perception of modified spectral tilt is essential. Second, it would be prudent to test older infants, between 12 and 18 months, to determine if the results observed for 9-month-old infants here, are indicative of a more advanced phase of speech perception or whether their performance is idiosyncratic, resulting from the intense period of linguistic reorganisation which occurs around this age. Despite the need for further research, this work clearly shows that 6- and 9-month-old NH infants respond in qualitatively different ways when listening to fricatives with modified spectral tilts, and that these differences reflect the developmental shift in speech perception that occurs between these ages. It seems that the increased linguistic sophistication of 9-month-old infants significantly impedes their ability to discriminate spectrally tilted speech contrasts, and if this is found to be the case with HI infants too, then this should be taken into consideration when optimising the intelligibility of the speech output of infants' hearing aids.

APPENDIX Q

Approximants manuscript

The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: II. Mid-frequency approximants

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Keywords: spectral tilt, infant development, speech perception, hearing aids, approximant discrimination

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Introduction

Fitting young HI infants with hearing aids presents a number of challenges, one of which is ensuring that the devices provide appropriate amplification for the perception of speech. Because infants are acquiring language, it is necessary to provide a signal that allows them to identify the contrastive phonemic distinctions that occur in their native language. To do this, HI infants need access to a wide range of frequencies across the speech spectrum. For instance, for fricative discrimination, they need access to high frequencies and for vowels, access to low frequencies. Current infant hearing aid prescriptions attempt to achieve access to the full spectrum (Cornelisse et al., 1995) by maintaining the natural spectral tilt of speech, which has a spectral slope of -3 to -5 dB per octave above 800 Hz (Byrne et al., 1994). However, this strategy has not been empirically tested. It might be the case that for HI infants, better intelligibility is achieved from speech with high-frequency emphasis (positive spectral tilt) or even low-frequency emphasis (negative spectral tilt). To investigate this issue, NH infants' perception of acoustically modified speech was examined. This research will lay the foundation for future testing of HI infants and provide direction as to the research priorities that should be pursued with respect to HI optimising infants' amplification.

Until recently, scant attention had been paid to how NH infants perceive spectral tilt applied to speech, although there is research on infant spectral tilt discrimination using complex tones (Clarkson, 1996; Tsang & Trainor, 2002). Researchers in our laboratory have completed two initial studies which show that, firstly, NH infants can discriminate speech with high- or low-frequency emphasis from unmodified speech when the tilt factor is large ($\pm$9 dB/octave), but when the tilt is reduced to $\pm$6 dB/octave, 6-month-old infants discriminate speech only in the negative tilt condition, and 9-month-old infants discriminate speech only in the positive tilt condition (Kitamura et al., accepted with revisions). The second study showed that, in general, NH infants prefer listening to positively tilted speech rather than unmodified speech, and they prefer unmodified speech over negatively tilted speech (Kitamura et al., submitted).

More critical to the study reported here is the previous investigation which examined how modifying the spectral tilt of the high-frequency fricative contrast /f/-/s/ affected discrimination by 6- and 9-month-old NH infants. The results revealed that 6-month-old infants could discriminate the fricatives, irrespective of whether they remained unmodified or had high- or low-frequency emphasis. On the other hand, older infants could discriminate the contrast only when it was unmodified, with its natural spectral slope intact. It is argued that the differences observed in the discrimination performance of 6- and 9-month-old infants arise because of developmental differences in the way infants perceive speech. At 6 months of age, infants are still in the early phase of speech perception, which is acoustically, rather than linguistically, driven. This acoustic mode of perception underlies the ability of younger infants to discriminate a wide range of both native and non-native speech contrasts (Eimas et al., 1971; Trehub, 1976), and their lack of language-specific sensitivity to native-language consonants (Pegg & Werker, 1997). On the other hand, older infants discriminate /f/-/s/ only in its natural, unmodified form because their linguistically driven speech perception constrains them to more exact language-specific spectral profiles of the consonant contrast. Evidence shows that around this age, perceptual reorganisation occurs such that there is a decline in the discrimination of contrasts that are not phonemic in the native language (Werker & Tees, 1984), and an improvement in the discrimination of native-language phonemic categories (Kuhl et al., 2008). Moreover, infants of this age are paying less attention to the prosodic aspects of speech, and more attention to the phonetic and phonotactic details of their native language (Friederici & Wessels, 1993).

The fact that older NH infants' speech perception is more constrained than that of younger infants might have implications for HI infants. That is, older HI infants may have more specific amplification requirements than younger infants, who might adapt more readily to spectrally tilted amplified speech. Of course, no testing has yet been conducted with HI infants. Furthermore, it is also unknown whether the developmental effect found for fricative discrimination is indicative of a generalised effect that applies to a range of speech contrasts, or whether it is peculiar to those consonants whose energy is concentrated in the high-frequency region. Thus, the goal of the current study was to extend the findings of the fricative study to a new class of sounds, characterised by a concentration of energy in the lower frequencies: approximants. Although classed as consonants, approximants are produced in a vowel-like manner and exhibit characteristic formant patterns (Harrington & Cassidy, 1999). The most notable acoustic difference between /r/ and /l/ is in the frequency value of the third formant (F3). Whereas /r/ is characterised by a low F3 (between 1300 and 1800 Hz for males, higher for females), and a corresponding steep transition into the adjacent vowel, the F3 of /l/ is higher, and often difficult to identify due to the attenuating effect of an antiresonance that occurs around the same frequency (Harrington & Cassidy, 1999).

Infants' discrimination of the English approximant contrast /r/-/l/ follows the typical course of development for consonant perception. In the early months, both native (Eimas, 1975; Karzon, 1985) and non-native (Kuhl et al., 2006; Tsushima et al., 1994) infants can discriminate /r/-/l/. As infants begin to attune to their native language, their discrimination improves such that English 10- to 12-month-old infants outperform a younger group of 6- to 8-month-old infants, which may be attributed to their extra native-language experience (Kuhl et al., 2006). In contrast, by 10-12 months, Japanese infants can no longer discriminate /r/-/l/ because it is not a phonemic contrast in Japanese.

In the current study, 6- and 9-month-old NH infants were tested for their discrimination of the /r/-/l/ contrast in one of three conditions: unmodified normal speech; speech with a positive 6 dB/octave spectral tilt; or speech with a negative 6 dB/octave spectral tilt. Modifying the natural spectral tilt of approximants has an impact on their distinctive acoustic attributes. When positive spectral tilt is applied, the intensity of frequency information above 1000 Hz is increased, and this might be expected to facilitate discrimination because it amplifies the part of the spectrum where the difference between the two approximants occurs, that is, at F3 (around 2000 to 3000 Hz). The negative tilt, on the other hand, would be expected to have the opposite effect as it reduces emphasis to the higher frequencies and may therefore obscure the differences between the approximants and make discrimination difficult. Over and above these acoustic-based predictions, it was also expected that the results of the current study would replicate the results of the fricative study. That is, 6-month-old infants, who perceive speech in a language-general acoustic manner, would discriminate /r/ and /l/ regardless of the spectral tilt condition, while the older infants, who have progressed from a language-general to a language-specific mode of speech perception, would find that negative and positive spectral tilts interfere with the stimuli such that discrimination is not possible.

Methods

NH infants aged 6 and 9 months were tested for their discrimination of /r/ and /l/ using an habituation-dishabituation procedure. Each approximant was paired with the high-frequency Australian-English long vowel /iː/ to create CV monosyllabic stimuli: /riː/ and /liː/. Infants were assigned to one of three conditions: (i) Normal Speech, in which /riː/-/liː/ was presented in an unmodified form; (ii) Negative Tilt, in which spectral tilt was applied to /riː/-/liː/at -6 dB/octave; or (iii) Positive Tilt, in which spectral tilt was applied to /riː/-/liː/ at +6 dB/octave.

Participants

A final sample of 96 infants participated in the study. Sixteen infants were unable to complete the task and their data were excluded. Full participant details are provided in Table 1. All infants were recruited from English-speaking homes through an advertisement in *Sydney's Child* magazine. Parents reported that their infants had successfully passed their newborn hearing screen, did not suffer from ear infections and were well on the day of testing. All participants were reimbursed for their travel costs and received a small gift.

Condition	Σ	Age (months)		Data not included (n)
	(n)	M	Range	Failed to habituate
Normal Speech	16	6.0	5.5 – 6.4	3
	16	8.9	8.6 – 9.3	1
Negative Tilt	16	6.1	5.7 – 6.5	2
	16	8.8	8.6 – 9.3	5
Positive Tilt	16	6.0	5.6 – 6.5	-
	16	8.9	8.6 – 9.3	5

Table 1. Mean age, age range of participants, and rate of task completion for each condition.

Speech Stimulus materials

The speech stimuli were four natural tokens each of /liː/ and /riː/ recorded by an adult female speaker of Australian English. Four measures were taken for each token: total duration, F0 at the vowel midpoint, frequency of F3 at the point of its onset, and F3 at the vowel midpoint (Table 2). Measures of duration, F0, and F3 at vowel midpoint were well matched amongst all tokens of /liː/ and /riː/, but the tokens differed markedly on the critical F3 onset measure.

Stimulus	Duration (msec)	F0 at vowel midpoint (Hz)	F3 at onset (Hz)	F3 at vowel midpoint (Hz)
/liː/	669 (26)	150 (0.5)	3005 (93)	3200 (23)
/riː/	645 (29)	149 (3)	2059 (55)	3164 (43)

Table 2. Mean acoustic measures averaged across four tokens of /liː/ and /riː/.
The syllables differ by approximately 1000 Hz on the F3 onset measure. Standard deviations are in parentheses.

As in the earlier fricative study, two FFT filters were applied to the approximants to produce the stimuli for the Positive and Negative Tilt conditions, and the original unmodified speech tokens were used as stimuli in the Normal Speech condition. Figure 1 shows the long-term average speech spectra for the approximants in each of the three conditions. Full details of the filtering procedure can be found in the fricatives paper.

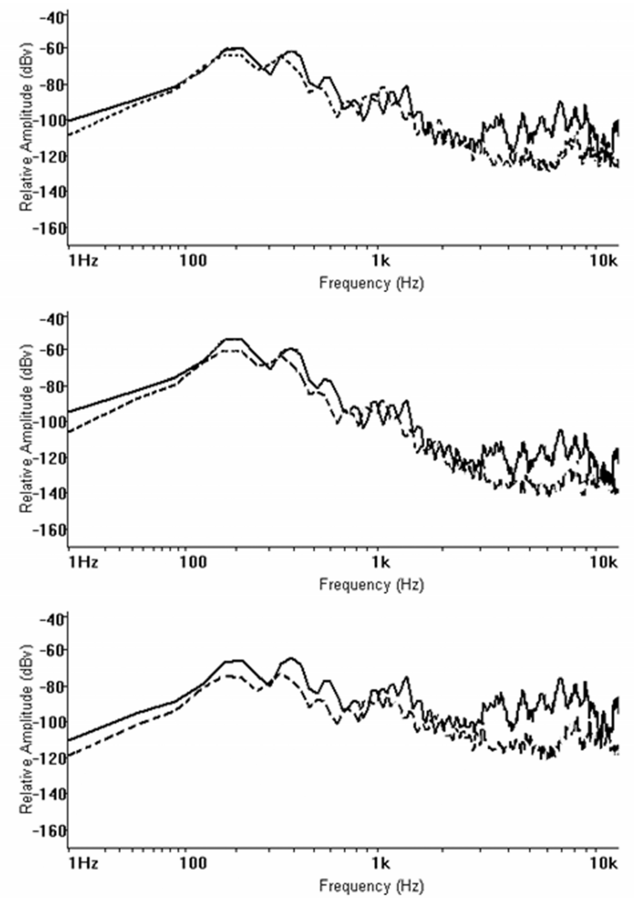

Figure 1. Long-term average speech spectra of approximant portions of single tokens of /riː/ and /liː/. Dotted line is /r/ and solid line is /l/. The top panel is Normal Speech. The middle panel shows Negative Tilt with greater relative amplitude of energy below 1000 Hz compared to energy above 1000 Hz. The bottom panel shows Positive Tilt, which boosts the amplitude of the high-frequency region above 1000 Hz at the expense of the low-frequency below 1000 Hz.

Materials and Apparatus

The experiment was conducted in the same test rooms and with the same equipment used in the fricative study. For full details, please see the fricatives paper.

Procedure

Discrimination was tested by using the infant-controlled habituation-dishabituation procedure used in the earlier fricative study. Full details can be found in the fricatives paper.

Results

Fixation Durations

The mean fixation durations in (i) the last two habituation trials; (ii) the two no-change control trials; and (iii) the two novel test trials were calculated for each infant in each of the three conditions. Means and standard errors for each age group in each of the conditions are shown in Figure 2.

For each condition, a 2 (age) x (3) (trial type) ANOVA was conducted with two planned contrasts. The first contrast was to verify that there was no recovery in fixation duration in the control trials following the habituation trials. The second contrast tested whether or not the infants discriminated the two stimulus sounds, i.e., whether fixation durations were longer in test trials compared to control trials. Where there were significant interactions and main effects for trial type, simple effects tests were performed to ascertain which of the two age groups discriminated the approximant contrast in each condition.

In all three conditions, the contrast which tested whether there was a fixation recovery in control trials confirmed there were no differences in fixation durations between habituation and control trials, all ps > 0.2. That is, both age groups habituated in each of the three conditions. The results for the contrast which tested whether infants discriminated /r/-/l/ in each of the three conditions are detailed below.

Normal Speech Condition

The results of the ANOVA showed a significant main effect for trial type indicating that fixation duration increased in test trials (M_{test} = 7.2 sec) compared to control trials (M_{con} = 4.7 sec), $F(1,30) = 9.42$, $p < 0.01$, $\eta_p^2 = 0.24$. The main effect for age and age x trial type interaction were not significant. Simple effects tests confirmed that both 6-month-old, $F(1,30) = 4.99$, $p < 0.04$, and 9-month-old infants, $F(1,30) = 4.71$, $p < 0.04$, had longer fixation durations in test compared to control trials. Thus, both age groups were able to discriminate /r/-/l/ in the Normal Speech condition.

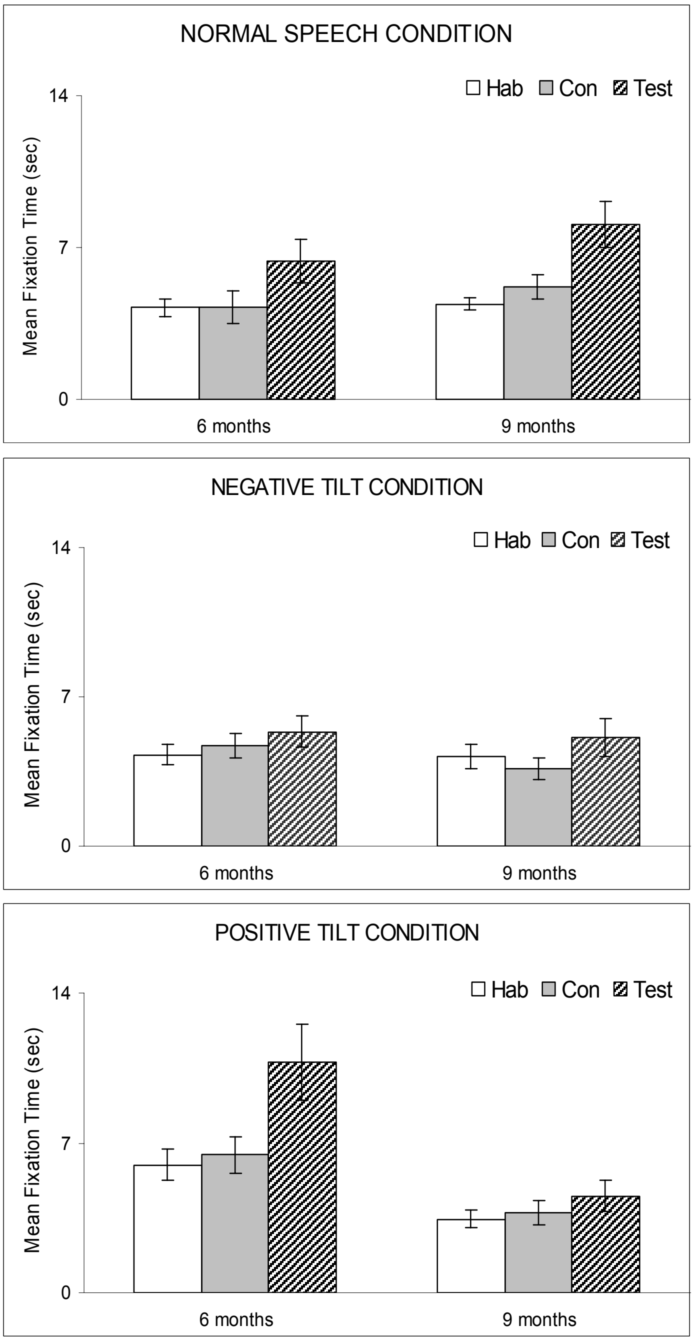

Figure 2. Mean fixation times for 6- and 9-month-old infants.
Top: Normal Speech condition, Middle: Negative Tilt condition, Bottom: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

Negative Tilt Condition

In this condition the ANOVA showed no significant main effect for trial type, indicating that there was no difference in fixation duration between test trials (M_{test} = 5.2 sec) and control trials (M_{con} = 4.2 sec), $p > 0.07$. Neither was the main effect for age or age x tilt type interaction significant. Thus, both age groups failed to discriminate /r/-/l/ when low-frequency information was emphasised in the Negative Tilt condition.

Positive Tilt Condition

In the Positive Tilt condition, the ANOVA results revealed a significant main effect for trial type, $F(1,30) = 9.81$, $p < 0.01$, $\eta_p^2 = 0.25$, and age, $F(1,30) = 14.94$, $p < 0.001$, $\eta_p^2 = 0.33$, and a significant age x trial type interaction, $F(1,30) = 4.66$, $p < 0.04$, $\eta_p^2 = 0.13$. Averaged across trial types, 6-month-olds ($M_{6mo} = 7.7$ sec) looked longer than 9-month-olds ($M_{9mo} = 3.9$ sec); and averaged across age groups, infants showed a recovery in fixation durations during test trials ($M_{test} = 7.6$ sec) compared to control trials ($M_{con} = 5.1$ sec). However, the significant interaction revealed that 6-month-old infants had a larger increase in fixation durations than 9-month-old infants. Simple effects test results were significant for 6-month-old infants, $F(1,30) = 7.92$, $p < 0.01$, but not 9-month-old infants, $F(1,30) = 2.04$, $p > 0.16$. Thus, in the Positive Tilt condition, younger successfully discriminated /r/-/l/ when high-frequency emphasis was added, whereas their older counterparts were unable to do so.

Discrimination Indices

The results show that both 6- and 9-month-old infants could discriminate the /r/-/l/ contrast when it was presented in the Normal Speech condition. In the Positive Tilt condition, 6-month-old infants discriminated /r/-/l/, whereas 9-month-old infants failed to discriminate the contrast. Interestingly, neither group could discriminate the contrast in the Negative Tilt condition. Thus, it seems that, overall, 6-month-old NH infants are better than 9-month-olds at discriminating speech under altered spectral tilt conditions, but these results do not tell us in which particular condition 6-month-old infants performed best. To investigate each group's relative discrimination performance across the three conditions, additional analyses were conducted using DIs as described in the earlier fricative study. A DI is calculated by expressing fixation duration in test trials as a proportion of fixation duration in both control and test trials. Any group with a mean DI between 0.5 and 1 indicates that the group discriminated /r/-/l/, with higher DIs indicating a stronger preference for the novel (test) stimulus. A DI was calculated for each infant and the mean DI for each age group and condition are shown in Figure 3.

Each group's mean DI was compared to chance (0.50) and one-tailed t-tests revealed that the 6-month-olds' DIs were above chance in the Normal Speech and Positive Tilt conditions only, *p*s < 0.02. For 9-month-olds, the DI exceeded chance in the Normal Speech condition only $t(1,15) = 2.04$, $p < 0.03$. These results are in agreement with the fixation duration results presented earlier. Both age groups discriminated /r/-/l/ when the contrast was unmodified, neither group discriminated when negative tilt was applied, and only the 6-month-olds discriminated in the Positive Tilt condition.

To compare discrimination performance across conditions, the DIs of infants in both age groups were analysed in a univariate 2 (age) x 3 (condition) ANOVA. Planned contrasts were included to test for linear and quadratic trends across the three equally spaced conditions: Negative Tilt (tilt factor: -6), Normal Speech (tilt factor: 0), and Positive Tilt (tilt factor: +6). The purpose of these contrasts was to determine whether there was a linear improvement in discrimination performance as tilt factor increased, as was found in the 6-month-old group in the fricative study or whether the DIs for each condition followed a quadratic trend. Although no significant results were found here, it is worth noting that the mean DIs, as shown in Figure 3, follow the same trends found for fricatives. That is, discrimination performance for 6-month-old infants improved from Negative to Positive Tilt, while for 9-month-old infants, discrimination in the Normal Speech condition was superior to that of the two spectral tilt conditions.

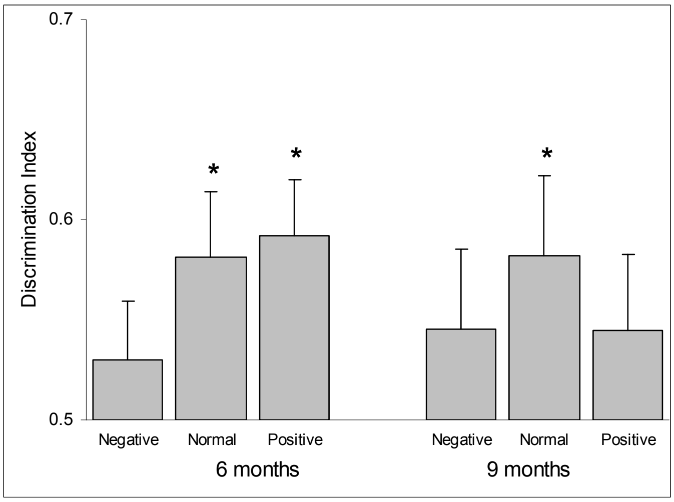

Figure 3. Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

In summary, the results show that 6-month-old infants can discriminate /r/-/l/ in the Normal Speech and Positive Tilt conditions, whereas 9-month-old infants can discriminate /r/-/l/ only when the spectral tilt is unmodified. An examination of DIs suggests that the same general trends found for fricatives occurred for approximants, that is, 6-month-old infants' discrimination performance improves as the degree of tilt increases, while 9-month-old infants perform best in the Normal Speech condition. However, these trends were not significant in the case of approximants.

Discussion

The results show that both 6- and 9-month-old NH infants discriminated /r/-/l/ in the Normal Speech condition. However, when a positive 6 dB/octave spectral tilt was applied to the approximants, younger but not older infants discriminated the contrast, and when a negative 6 dB/octave spectral tilt was applied, neither group could do so. The failure of 9-month-old infants to discriminate /r/-/l/ with either +6 or -6 dB/octave spectral tilt is in accord with the result reported for the fricative contrast /f/-/s/. Thus, for both high- and mid-frequency speech sounds, older infants demonstrate an inability to discriminate spectrally tilted phonemic contrasts.

For 6-month-old infants, the results of the fricative study were partially supported. In this study, younger infants showed more flexible discrimination abilities than older infants, given that they could discriminate /r/-/l/ in both the Positive Tilt and Normal Speech conditions. However, this time, the 6-month-olds found the Negative Tilt condition problematic. As noted earlier, the application of negative spectral tilt increases the amplitude of low-frequency energy and de-emphasises the F3 difference between the two sounds. This amplitude imbalance (Figure 1) may have resulted in, not only a reduction in the prominence of the critical formant information, but perhaps also a masking effect, whereby the louder low-frequency information suppresses the now quieter, yet critical high-frequency information, thus rendering the contrast too difficult for all infants in the Negative Tilt condition.

Importantly, the results of this study strengthen the conclusions drawn in the earlier study regarding the developmental link between infants' responses to spectral tilt and the early stages of language acquisition. Previously with high-frequency fricatives, and now with mid-frequency approximants, it has been shown that younger infants find discriminating spectrally tilted speech contrasts relatively easy, while older infants' ability to discriminate fricatives and approximants is restricted to their presentation as natural, unmodified speech. This narrowing of the infant's linguistic focus between 6 and 9 months of age is entirely consistent with the developmental change in speech perception that occurs between these ages. That is, in the first six months, infants operate in an acoustic-auditory mode and perceive both native and non-native speech sounds equally well (Eimas et al., 1971; Trehub, 1976). By the time infants reach 9 months, they are on the verge of perceptual reorganisation, in which native phoneme categories are consolidated and those that are non-phonemic are excluded. That is, in this important phase of language development, 9-month-old infants demonstrate improved perception of native speech sounds at the expense of irrelevant sounds from other languages (Kuhl et al., 2008; Werker & Tees, 1984).

In the earlier study on fricatives, it was suggested that the inability of older infants to perceive speech contrasts with modified spectral tilts might imply that older HI infants would benefit from amplification strategies that emulate the natural speech spectrum as closely as possible, whereas for younger infants, this may not be so critical. Although future studies with HI infants are necessary before any firm conclusions can be drawn, the results of the current study lend further support to this preliminary recommendation. However, the failure of younger infants to discriminate /r/-/l/ in the Negative Tilt condition shows that in some cases, a modified spectral tilt can interfere with the acoustic differences between sounds and lead to perceptual difficulties. Thus, perhaps the optimal amplification strategy for both younger and older infants will prove to be one that preserves the natural spectral shape of speech as closely as possible.

In summary, this study confirms that 6- and 9-month-old NH infants respond to modified spectral tilts in distinctly different ways that reflect the transformation that occurs in speech perception during the infant's first year. In order to complete the picture of how spectral tilt affects discrimination of sounds across the full speech spectrum, a third study has been conducted investigating the effect of spectral tilt on NH infants' discrimination of a low-frequency vowel. Should the effect of spectral tilt prove consistent across high-, mid- and low-frequency speech sounds, we will be well-placed to draw conclusions about NH infants' perception of acoustically modified speech across the frequency spectrum.

APPENDIX R

Vowels manuscript

The emergence of sensitivity to spectral tilt by 9 months has implications for infants' hearing aids: III. Low-frequency vowels

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Keywords: spectral tilt, infant development, speech perception, hearing aids, vowel discrimination

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Introduction

Most infants with HL are now fitted with hearing aids very early in life, and although these infants develop better spoken language abilities than late-identified children (Yoshinaga-Itano et al., 1998), many children with early-identified HL still exhibit delayed language acquisition compared to peers with NH (Moeller et al., 2007a; Moeller et al., 2007b). This suggests that there are a number of variables that contribute to how well HI children develop spoken language. One of these is the intelligibility of the amplified speech that infants hear through their hearing aids, which, in part, depends on the spectral shape or tilt of the amplified speech signal. Current practice in many centres is to fit young infants with hearing aids that maintain the natural loudness balance between low- and high-frequency regions (Cornelisse et al., 1995), thus preserving the natural slope of speech, which is between -3 and -5 dB/octave above 800 Hz (Byrne et al., 1994). However, until now there has been little research to support whether this approach or other alternatives provide better speech intelligibility for infants. It may be the case that amplification which emphasises the low-frequency region of the speech spectrum (negative spectral tilt) or the high-frequency region (positive spectral tilt) is beneficial for infants. The focus of this research is to determine whether positive, negative, or no spectral tilt optimises NH infants' ability to discriminate contrastive segments in their native language. This information can then be used to guide future research with HI infants. Thus, this study, together with the two previous studies, represents the first step towards providing a benchmark against which to compare HI infants' perception of acoustically modified speech.

A further issue that has not yet been investigated is whether infants' amplification needs change as they acquire language over the course of the first year. Early in life, NH infants perceive speech in an acoustic/auditory mode (Aslin & Pisoni, 1980; Burnham, 1986), and discriminate a wide range of both native and non-native speech sounds (see Saffran et al., 2006). They have an early reliance on the low-frequency aspects of speech: its prosodic, rhythmic and affective characteristics – they not only prefer these characteristics (Fernald & Kuhl, 1987; Kitamura & Burnham, 1998; Panneton et al., 2006), but also use them to recognise their native language (Mehler et al., 1988; Nazzi et al., 2000). During this early phase, they also start attuning to native-language vowels which are situated in the low-frequency region of the speech spectrum (Kuhl et al., 1992; Polka & Werker, 1994). However, by 9 months of age, infants are undergoing perceptual reorganisation, and beginning to perceive speech in a more language-specific mode. By this stage, they have acquired substantial experience with their native language and are now attuning to the high-frequency segmental aspects of language, that is, native-language consonants (Werker & Tees, 1984), and the phonotactic rules of the native language (Friederici & Wessels, 1993; Jusczyk et al., 1993b; Morgan & Saffran, 1995).

To explore how NH infants in the early phases of language development perceive altered spectral tilt, our laboratory completed two studies (Kitamura et al., submitted; Kitamura et al., accepted with revisions), which examined spectral tilt applied to speech, rather than complex tones (Clarkson, 1996; Tsang & Trainor, 2002). The first study examined infants' ability to discriminate speech with a positive or negative tilt from normal unmodified speech (Kitamura et al., accepted with revisions). The results showed that, when the spectral tilt was applied at ±9 dB/octave, both 6- and 9-month-old infants discriminated the tilted speech from normal speech. However, when the tilt was reduced to ±6 dB/octave, the younger infants could discriminate only speech with a negative tilt (low-frequency emphasis) from normal speech, while 9-month-old infants were more likely to discriminate speech with a positive spectral tilt (high-frequency emphasis) from the normal speech. The second study examined infants' preferential attention to speech with altered spectral tilts, and the results for 6-month-old infants were similar but less robust than those for 9-month-old infants (Kitamura et al., submitted). Six-month-old infants preferred normal speech to speech with a low-frequency emphasis, but showed undifferentiated attention when speech with a high-frequency emphasis was paired with normal speech. However, at 9 months, infants displayed a preference for speech with a positive tilt over normal speech and normal speech over speech with a negative tilt. Together, the results of these two studies show that, over time, infants become more focussed on the high-frequency aspects of speech, just as one would expect from infants who are starting to perceive speech in a language-specific mode and consolidating their native-language consonant categories.

The finding that NH infants show preferential attention for speech with a high-frequency emphasis implies that hearing aids with a positive spectral tilt might provide the best sound quality, particularly for older HI infants. Although sound quality is an important consideration, more important for infants in the throes of language acquisition is speech intelligibility. Thus, in this series of studies, three experiments were conducted investigating how spectral tilt influences 6- and 9-month-old NH infants' ability to discriminate native-language speech sounds. The first study examined infants' discrimination of the high-frequency fricative contrast /f/-/s/ under positive tilt, negative tilt and normal speech conditions, and in the second study, infants' discrimination of the mid-frequency approximant contrast /r/-/l/ under the same three conditions. As expected, there was a developmental difference in the way younger and older infants discriminated fricatives and approximants with modified spectral tilts. Nine-month-old infants discriminated the fricative and approximant contrasts only when presented as unmodified normal speech, not with a positive or negative spectral tilt. In contrast, younger infants discriminated the fricative contrast, irrespective of whether it was unmodified, or had high- or low-frequency emphasis. The younger infants were also able to discriminate the approximant contrast in the unmodified and positive tilt conditions. These results are indicative of the different developmental stages of the two age groups. It seems that because 6-month-old infants perceive speech in an acoustic/auditory mode, they demonstrate malleability when discriminating speech sounds with modified tilts. Nine-month-old infants, on the other hand, are starting to internalise the native-language phonemes and phonotactic rules of their native language, and are on the verge of operating in a language-specific mode. Therefore it is not surprising that they discriminate the speech contrasts only in their unmodified form.

Having demonstrated the influence of spectral tilt on NH infants' discrimination of a high-frequency and a mid-frequency consonant contrast, the goal of the current study was to extend these findings to a low-frequency vowel contrast. As mentioned earlier, native vowel perception precedes consonant perception. Young infants aged up to 4 months can discriminate both native (Trehub, 1973) and non-native vowel contrasts (Polka & Werker, 1994). However, by 6 months, they start to treat non-native vowels differently to native ones. For example, Kuhl et al. (1992) showed that, like adults, American 6-month-old infants perceive the American English front unrounded vowel /i/ as a prototype vowel, but not the non-native Swedish rounded front vowel /y/, whereas Swedish infants demonstrate the opposite pattern, treating the Swedish /y/ as a prototype, but not the American English vowel /i/. Native-language prototype vowels act as magnets, whereby less prototypical vowels from the same category are regarded as more similar to the prototype vowel than to each other, even when all the vowels are equidistant acoustically (Kuhl et al., 1992).

In the current study, an Australian English vowel contrast was used: /ɔ/ (as in 'hot') and /ɐ/[7] (as in 'hut'), which are short, lax monophthongs, adjacent to one another in the lower right portion of F1-F2 vowel space. Rounded /ɔ/ is a back vowel; unrounded /ɐ/ is lower, and not as far back. At least two infant perception studies have used similar vowel contrasts. Kuhl (1983) showed that by 6 months, infants have well-defined and relatively robust categories for the American English vowels /ɑ/ as in 'cot' and /ɔ/ as in 'caught,' which are unaffected by variations in gender, age and pitch contour. A second study by Bohn (2007) using the Southern British vowels, /ʌ/ and /ɒ/, was motivated by consistent reports of asymmetry in vowel perception, whereby infants tend to perceive two different vowels as members of the same category when the more peripheral vowel is followed by the less peripheral vowel, rather than the other way round (Polka & Bohn, 2003). These peripheral vowels exert a 'magnet' effect that is similar to that of the native-language vowel prototypes described above (Kuhl et al., 1992). Bohn (2007) used a conditioned head turn procedure to show that Danish-learning infants aged between 6 and 11 months categorised the non-native vowels /ʌ/ and /ɒ/ as the same when the more peripheral vowel /ʌ/ was presented as the background stimulus, but not when the order of presentation was reversed. Although these two studies differ from the current study in terms of methods and motivation, together they indicate that the vowel contrast selected here should be discriminable by infants aged 6 months and older, when presented in its unmodified form.

[7] Earlier Australian English transcription systems have transcribed /ɔ/ as /ɒ/ and /ɐ/ as /ʌ/. This study uses the updated Australian English transcription system proposed by Harrington, Cox and Evans (1997).

A between-participants design was used to test infants' discrimination of /ɔ/ versus. /ɐ/ in one of three conditions: (i) normal unmodified speech; (ii) with a positive spectral tilt; and (iii) with a negative spectral tilt. As in the previous consonant studies, application of a positive spectral tilt increased the amplitude of the high-frequency speech information above 1000 Hz, and a negative tilt increased the amplitude of the frequencies in the lower range of the speech spectrum below a fulcrum of 1000 Hz. On the basis of the previous results, it was expected that 9-month-old infants would distinguish /ɐ/ and /ɔ/ only when presented in its unmodified form. On the other hand, three different outcomes were possible for 6-month-old infants. They would either discriminate the vowel contrast: (a) in all three conditions as they did in the fricatives study; (b) only in the unmodified and negative tilt conditions because negative tilt is the one that adds emphasis to the low-frequency portion of the spectrum where the first two formants, which differentiate the vowels, are located (Delattre, Liberman, & Cooper, 1951; Peterson & Barney, 1952); or (c) only in the unmodified condition because attunement to native vowels occurs earlier than for consonants, and thus 6-month-olds may already be attending more exclusively to vowels with a normal spectral profile.

Methods

An habituation-dishabituation procedure was used to test 6- and 9-month-old NH infants' discrimination of the vowel contrast /ɐ/-/ɔ/. Each vowel was followed by the voiceless stop /t/, forming VC monosyllables, /ɔt/ and /ɐt/. Infants were allocated to one of three conditions: (i) Normal Speech, in which /ɐt/-/ɔt/ was presented unmodified; (ii) Negative Tilt, in which spectral tilt was applied to /ɐt/-/ɔt/ at -6 dB/octave; or (iii) Positive Tilt, in which spectral tilt was applied to /ɐt/-/ɔt/ at +6 dB/octave.

Participants

A final sample of 96 full term infants participated in the study. Thirty-six infants failed to complete the task and their data were excluded. Full participant details are shown in Table 1. Participants were recruited via an advertisement in *Sydney's Child* magazine. English was the primary language of all families in the study and parental reports indicated that each infant had passed their newborn hearing screening test, did not suffer from ear infections and was well on the day of testing. Participants were reimbursed for their travel costs and received a small gift.

Condition	Σ	Age (months)		Data not included (n)	
	(n)	M	Range	Failed to habituate	Cried
Normal Speech	16	6.1	5.6 – 6.5	5	-
	16	9.1	8.7 – 9.4	6	1
Negative Tilt	16	6.1	5.5 – 6.5	1	1
	16	8.9	8.6 – 9.3	8	1
Positive Tilt	16	6.0	5.5 – 6.4	8	1
	16	8.9	8.5 – 9.3	4	-

Table 1. Mean age, age range of participants, and rate of task completion for each condition.

Speech Stimulus materials

The speech syllables were recorded by an adult female speaker of Australian English. Four exemplars each of /ɐt/ and /ɔt/ were selected as stimuli and subjected to acoustic analysis. For each token, syllable duration, F0 at vowel midpoint, and the frequencies of the first three formants at vowel midpoint were measured. As shown in Table 2, syllable duration and F0 were comparable amongst the tokens. The formant frequency values were comparable to those reported for Australian English vowels (Butcher, 2006; Cox, 2006), and while the vowels were well differentiated in terms of the low-frequency formants, F1 and F2, the frequency of F3 was similar for both vowels at approximately 2900 Hz. As in the earlier consonant studies, two FFT filters were applied to the vowels to modify their spectral tilt for use in the Positive and Negative Tilt conditions, and the original speech sample was used as stimuli in the Normal Speech condition. Figure 1 shows the impact of the spectral tilting process on the long-term average speech spectra of the vowels in each condition.

Stimulus	Duration (msec)	Measures at vowel midpoint			
		F0 (Hz)	F1 (Hz)	F2 (Hz)	F3 (Hz)
/ɐt/	528 (28)	172 (2)	894 (18)	1377 (19)	2926 (32)
/ɔt/	541 (33)	175 (9)	728 (22)	1072 (13)	2889 (29)

Table 2. Mean acoustic measures across four tokens of /ɐt/ and /ɔt/.
Standard deviations are in parentheses.

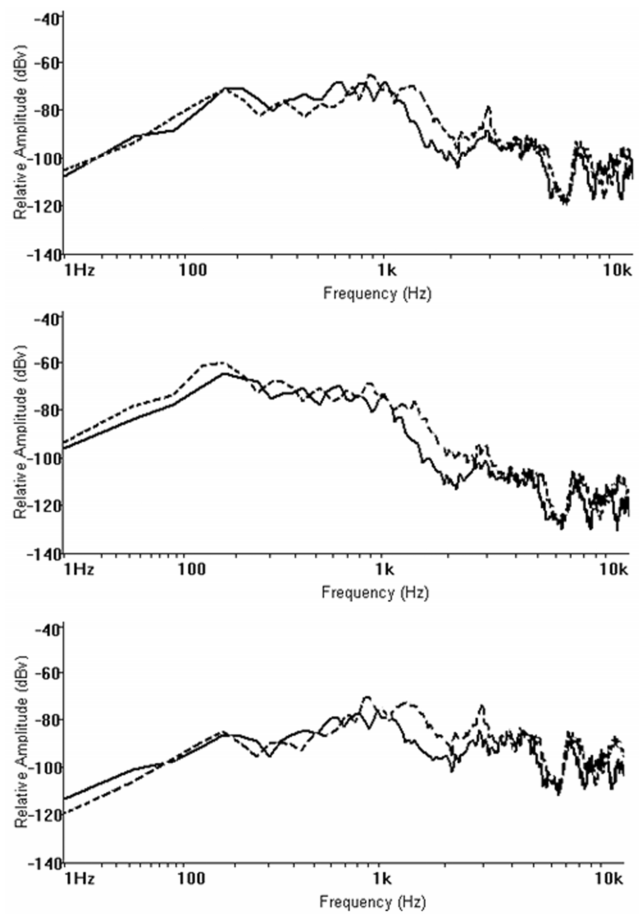

Figure 112. Long-term average speech spectra of vowel portions of single tokens of /ɐt/ and /ɔt/. Dotted line is /ɐ/ and solid line is /ɔ/. The top panel is the Normal Speech condition. The middle panel is the Negative Tilt condition, and shows the effect of applying emphasis to frequencies below 1000 Hz. The bottom panel is the Positive Tilt condition, which shows that emphasis has been applied above 1000 Hz.

Materials and Apparatus

Testing was conducted in the same environment and under the same conditions described in the earlier fricative study. Full details can be found in the fricatives paper.

Procedure

The same infant-controlled habituation-dishabituation procedure used in the fricative study was also used here. Please see the fricatives paper for a detailed description of the procedure.

Results

Fixation Durations

Mean fixation durations were calculated for (i) the last two habituation trials; (ii) the two no-change control trials; and (iii) the two novel test trials for each infant in each of the three conditions. Figure 2 displays the mean fixation durations for habituation, control, and test trials for 6- and 9-month-old infants in each of the three conditions.

For each condition, a 2 (age) x (3) (trial type) ANOVA was conducted with two planned contrasts. The first contrast tested the difference in fixation durations between habituation and control trials to confirm infants had habituated and did not show a fixation recovery in control trials. The second contrast tested the difference in fixation durations between control and test trials, that is, whether the infants had discriminated /ɔ/ and /ɐ/. Significant interactions and main effects for trial type were followed by simple effects tests to determine whether 6- or 9-month-olds were able to discriminate the vowels in each condition.

In all three conditions, the contrast testing recovery in control trials showed there were no significant differences in fixation durations between habituation and control trials, all *p*s > 0.08. Thus, all groups habituated successfully. The results for the contrast testing the difference between no-change control trials and test trials are reported below. Recovery in test trials was used to determine whether infants could discriminate /ɔ/-/ɐ/ in each of the three conditions.

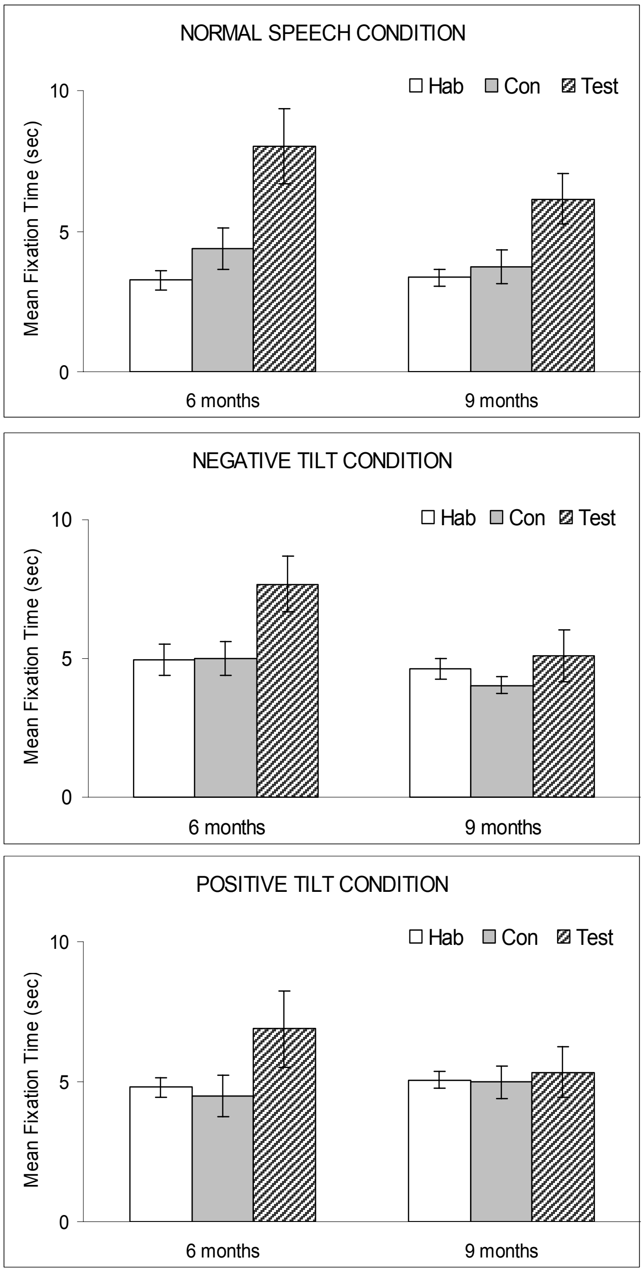

Figure 2. Mean fixation times for 6- and 9-month-old infants.
Top panel: Normal Speech condition, Middle panel: Negative Tilt condition, Bottom panel: Positive Tilt condition. Hab = habituation trials, Con = control trials, Test = test trials. Error bars = 1 standard error.

Normal Speech condition

The ANOVA showed a significant main effect for trial type, indicating an increase in fixation durations for test trials (M_{test} = 7.1 sec) compared to control trials (M_{con} = 4.3 sec), $F(1,30) = 13.81$, $p < 0.001$, $\eta_p^2 = 0.32$. There was no main effect for age or age x trial type interaction. Simple effects tests confirmed that infants at both 6 months,

$F(1,30) = 5.756$, $p < 0.02$, and 9 months, $F(1,30) = 16.43$, $p < 0.001$, had longer fixation durations in test compared to control trials. Thus, both younger and older infants discriminated the vowel contrast /ɔ/-/ɐ/ in the Normal Speech condition.

Negative Tilt Condition

The results for this condition also showed a significant main effect for trial type. Fixation duration was greater in test trials (M_{test} = 6.4 sec) compared to control trials (M_{con} = 4.5 sec), $F(1,30) = 5.97$, $p < 0.03$, $\eta_p^2 = 0.17$. The main effect for age was significant, $F(1,30) = 4.20$, $p < 0.05$, $\eta_p^2 = 0.12$, indicating that overall, 6-month-olds (M_{6mo} = 5.9 sec) looked longer than 9-month-olds (M_{9mo} = 4.6 sec). There was no age x trial type interaction. Simple effects tests showed that 6-month-old infants successfully discriminated the vowels in the Negative Tilt condition, $F(1,30) = 4.97$, $p < 0.04$; but the result for 9-month-old infants was not significant, $F(1,30) = 1.26$, $p > 0.27$. That is, younger, but not older, infants were able to discriminate /ɔ/-/ɐ/ when low-frequency emphasis was applied to the contrast in the Negative Tilt condition.

Positive Tilt Condition

In this condition there was no significant main effect for trial type, indicating that there was no increase in fixation durations during test trials (M_{test} = 6.1 sec) compared to control trials (M_{con} = 4.7 sec), $F(1,30) = 3.174$, $p > 0.08$, $\eta_p^2 = 0.10$. The main effect for age and the age x trial type interaction were also not significant. The difficulty infants experienced in this condition may have been caused by the positive tilt boosting the amplitude of the high-frequency region of the spectrum, while decreasing the amplitude of the low-frequency region, thereby obscuring the critical first two formants, which effectively differentiate these two vowels.

Discrimination Indices

These results show that both 6- and 9-month-old infants could discriminate /ɔ/-/ɐ/ when presented in the Normal Speech condition. Although only 6-month-old infants discriminated the vowels in the Negative Tilt condition, neither group could discriminate the contrast in the Positive Tilt condition. To gain a clearer picture of each age group's relative discrimination performance across the three tilt conditions, further analyses were conducted using DIs as the dependent variable. The DI is a number between 0 and 1, obtained by dividing each infant's fixation time in test trials by the sum of fixation time in both control and test trials (DI = test/test+control). A DI greater than 0.5 indicates discrimination and higher DIs reflect a stronger preference for the novel over the habituation stimulus. For each infant in each age group, a DI was calculated and the means for each age group and condition are shown in Figure 3.

One-tailed t-tests were conducted on the mean DIs to examine whether the DIs were above chance performance (0.50). The results revealed that both age groups' DIs were above chance in the Normal Speech condition, ps < 0.006. The only other significant result showed that 6-month-olds' DI in the Negative tilt condition exceeded chance, $t(1,15) = 2.61$, $p < 0.01$. Thus, the DI analysis supports the analyses of fixation durations in showing that 6-month-olds discriminates /ɔ/-/ɐ/ in the Normal Speech and Negative Tilt conditions, whereas 9-month-olds discriminated /ɔ/-/ɐ/ only in the unmodified condition.

Next, the DIs of all infants were analysed in a 2 (age) x 3 (condition) ANOVA and planned contrasts tested for linear and quadratic trends across the three conditions. It should be noted that the three conditions are equally spaced in terms of spectral tilt: Negative Tilt (tilt factor: -6), Normal Speech (tilt factor: 0) and Positive Tilt (tilt factor: +6). There were no significant main effects for age, linear trend for condition, or any interactions, but the quadratic trend was significant, $F(1,90) = 3.91$, $p = 0.05$. This result suggests that, for both 6- and 9-month-old infants, discrimination was strongest in the Normal Speech condition as shown in Figure 3. This similarity in the performance of 6- and 9-month-old infants lends support to prediction (c) because it suggests that there is an emerging ability for 6-month-old infants to perceive vowels in a more restricted manner, just as older infants do. That is, because native categories are established earlier for vowels than consonants, 6-month-old infants find that the Normal Speech condition is most conducive to discrimination.

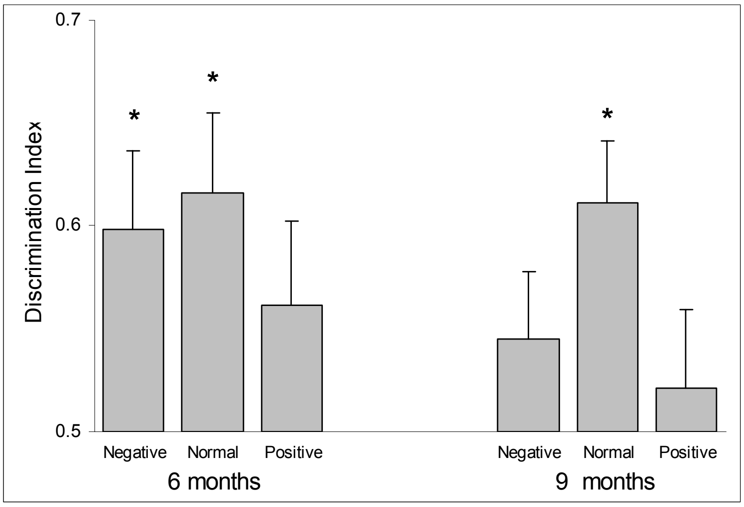

Figure 3. Discrimination indices for 6- and 9-month-old infants in Negative Tilt, Normal Speech and Positive Tilt conditions.
Both age groups show a quadratic trend. Asterisks indicate the mean DI is significantly greater than chance ($p < 0.05$). Error bars = 1 standard error.

In summary, the results show that 6-month-old infants can discriminate the vowels /ɔ/-/ɐ/ in the Normal Speech and Negative Tilt conditions, while 9-month-old infants discriminate /ɔ/-/ɐ/ only in the Normal Speech condition. Despite negative spectral tilt providing what should be helpful low-frequency emphasis, older infants fail to discriminate the vowel contrast in this condition. The DI analyses confirm that for 9-month-old infants, discrimination is best in the Normal Speech condition. Moreover, the DI analyses revealed that 6-month-old infants *also* performed best in the Normal Speech condition. This seems to reflect the fact that infants attune to native-language vowels before consonants, and hence 6-month-old infants are starting to find spectral tilt an unwelcome modification to vowels, just as older infants do with both consonants and vowels.

Discussion

The results revealed that 6- and 9-month-old NH infants discriminated the vowel contrast /ɔ/-/ɐ/ in the Normal Speech condition. However, in the Positive and Negative Tilt conditions, there were mixed findings. In the Positive Tilt condition, where high-frequency emphasis was applied to the vowels, neither age group could discriminate the contrast, whereas in the Negative Tilt condition, which provided low-frequency emphasis, only the 6-month-old group was successful. Thus, 6-month-old infants could discriminate vowels in both Negative Tilt and Normal Speech conditions, but the 9-month-old infants only in the Normal Speech condition.

In this study and in the previous investigations of the effect of spectral tilt on NH infants' ability to discriminate fricative and approximant contrasts, 9-month-old infants have consistently demonstrated that they can discriminate speech contrasts *only* in the Normal Speech condition. It seems that both positive and negative spectral tilts adversely affect older infants' ability to discriminate speech contrasts, even when the tilt emphasises acoustically useful information, that is, high-frequency emphasis for consonants, and low-frequency emphasis for vowels. Clearly, when faced with the task of discriminating vowel and consonant contrasts, older infants cannot accommodate modified spectral slopes, and can only discriminate those sounds which maintain the natural speech spectrum. It is possible that, for 9-month-old infants, altering the spectral tilt of speech sounds results in speech that seems non-native, or like poor exemplars of native speech categories. Whether or not this is the case, the results indicate that 9-month-olds are particularly sensitive to any deviations from the normal speech spectrum, and their speech discrimination suffers as a consequence.

In contrast to their older counterparts, younger infants have repeatedly shown that they can discriminate contrasts with altered spectral tilts. In the previous two studies with fricatives and approximants, the discrimination performance of younger infants improved when positive spectral tilt was applied because positive tilt emphasised the crucial high-frequency cues which differentiated the stimuli. In the current vowel study, the stimuli differed in the low-frequency portion of the speech spectrum where F1 and F2 are located, and when this region was emphasised in the Negative Tilt condition, the younger infants' discrimination performance was similar to their performance in the Normal Speech condition. The fact that younger NH infants are able to discriminate speech when the spectral tilt emphasises critical regions of the speech spectrum might be of particular interest to early interventionists because it suggests that in the first few months of life, HI infants might also respond to enhanced acoustic features, which could be used to highlight the differences between phonemes and assist young HI infants to discriminate and identify them.

In addition to any practical application of spectral tilt, it is important to highlight how the effect of spectral tilt on younger and older infants' discrimination patterns is accounted for by theories of infant speech perception (e.g., Aslin & Pisoni, 1980; Kuhl et al., 2008; Werker & Curtin, 2005). In her expanded version of the Native Language Magnet theory, Kuhl et al. (2008) outlines the first two phases of language acquisition. In the initial phase, infants can discriminate the range of phonetic segments found in human language because they do so at an acoustic, rather than a phonetic or phonological level (Aslin & Pisoni, 1980). The second phase, which begins in the second half-year of life, is characterised by 'phonetic learning' – vowels first, and consonants second (Polka & Werker, 1994; Werker & Tees, 1984). During this stage, the infant's perceptual system undergoes reorganisation, and the infant's phonetic perception becomes aligned with the native language sound inventory, such that perception of native-language speech sounds improves, while perception of non-native sounds declines.

The perceptual versatility displayed by the younger infants in these studies indicates that they are still in the first language-general phase of language acquisition. Moreover, the fact that the 6-month-old infants discriminated vowels best in the Normal Speech condition supports earlier findings which show that phonetic learning for vowels occurs earlier than for consonants (Kuhl et al., 1992; Polka & Werker, 1994). This might also be the case for approximants which are classed as semi-vowels and have characteristic formant structures (Harrington & Cassidy, 1999). In the previous study, 6-month-olds could discriminate approximants only in the Normal Speech condition and the Positive Tilt condition which emphasised the relevant region of the speech spectrum, whereas fricatives were discriminated in all conditions. Nonetheless, in the case of vowels, and perhaps semi-vowels, younger infants appear to be showing signs that they will soon reach the point where spectral tilt hinders discrimination. The older infants are already at this point, immersed in the second phase of language acquisition and heavily influenced by the specifics of their native language. Because they are undergoing perceptual reorganisation and attuning to speech according to native-language phonemic categories, they no longer discriminate speech sounds based on acoustic cues, rather their perception is constrained towards native-language spectral profiles, and hence they discriminate only those sounds heard in the Normal Speech condition.

In future studies, it would be useful to test older infants on their ability to discriminate spectrally tilted speech in order to examine whether spectral tilt continues to impact on speech discrimination beyond 12 months. It may be that after an intense period of perceptual reorganisation infants will be able to accommodate modifications to spectral tilt. More importantly, there is a need to test whether HI infants respond to modified spectral tilts in the same way that NH infants do. But perhaps the most critical issue that needs addressing with HI infants is whether language acquisition progresses at the same rate and in the same manner as for NH infants. Past studies with HI infants and children tend to focus on whether they can discriminate or identify native-language speech sounds (e.g., Agung, Purdy, & Kitamura, 2005; Houston, Pisoni, Kirk, Ying, & Miyamoto, 2003). However, it would be of immense practical and theoretical value to know whether HI infants begin the process of perceptual reorganisation in parallel with their NH counterparts, and when they begin attuning to native-language consonant and vowel categories. That is, do infants with impaired hearing show an improvement in their perception of native-language speech contrasts, and critically, a decline in their ability to discriminate non-native speech sounds?

The results presented here, together with those of the first two studies in the series, provide compelling evidence that 6- and 9-month-old NH infants differ in their ability to perceive speech with modified spectral tilt. Younger infants are capable of discriminating spectrally tilted speech contrasts as long as the tilt does not obscure important acoustic differences between the sounds. However, 9-month-olds have consistently shown that they are only able to discriminate speech contrasts when they are unmodified by spectral tilt. Because the speech contrasts were carefully selected to be representative of sounds across the speech spectrum, it seems to be the case that older NH infants are incapable of discriminating spectrally tilted speech contrasts, regardless of their frequency characteristics.