The Role of Infant-Directed Speech in Language Development of Infants with Hearing Loss

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MPsych

A thesis submitted for the Degree of

Doctor of Philosophy

The MARCS Institute for Brain, Behaviour and Development

HEARing CRC

Western Sydney University

November, 2019

Acknowledgments

Firstly, I would like to thank my supervisory panel, without their expertise and guidance this thesis could not have been completed. I thank my principal supervisor Dr Marina Kalashnikova for her support, encouragement, advice, patience, and kindness throughout my candidature. Her guidance was invaluable at every stage of this project, and her feedback taught me to think like a researcher. I thank Professor Denis Burnham for his precious feedback to both theoretical and practical aspects of my research. I thank Dr Pelle Söderström and Dr Yatin Mahajan for introducing me to the EEG world and for providing me helpful advice in navigating through the maze of the EEG world.

Secondly, I would like to thank the MARCS Institute for Brain, Behaviour and Development for providing me with research equipment, and academic, administrative and technical support. To my wonderful colleagues and friends within MARCS, your support and friendship means a great deal to me. I am especially grateful to my office mates: Ruth Brookman, Jessica Tan, Nicole Traynor, Stacey Sherwood, and Jenny Yu. I am also grateful to other members of MARCS community: Tina Whyte-Ball, Yassine Frej, Gloria Pino-Escobar, Yanping Li, Julie Beadle, Juqiang Chen, Jenny Zeng, and Samra Alispahic. Thank you for your friendship, support, and kindness.

I would like to acknowledge the MARCS Institute Higher Research Degree Scheme, Western Sydney University, and the HEARing CRC for supporting my research financially. Also, I would like to thank "Dick Smith's Food" for supporting my relocation to Australia.

I would like to thank "The Shepherd Centre" in Sydney and Wollongong, "Hear and Say" in Brisbane for their help in recruitment of babies with hearing loss. I am especially grateful to MARCS Institute Baby Lab and to Maria Christou-Ergos, Hana Zjakic, Scott O'Loughlin, Caitlin Hooper, Jen Armstrong, Dr Christa Lam-Cassettari, Dr Benjawan

Kasisopa, Dr Liquan Liu, Dr Varghese Peter and Dr Anne Dwyer, who gladly taught me everything that I needed to know to conduct the experiments in Baby Lab. Thank you for a wonderful Baby Lab experience.

Heartfelt thanks go to mothers and babies who participated in this study. This thesis would not be possible without you.

I would like to thank Zoran Djoric, my High School Psychology teacher, who introduced me to the Psychology world. Thank you for teaching me to believe in myself and for teaching me that with hard work I can achieve my dreams.

I am ever grateful to my family for their love, support, and encouragement, and for believing in me. To my sister Bojana, and to my nieces Masha, Jana, Neda, and Lenka, I am so lucky to be your sister and aunt. To Slavisa, who has supported me all the way through this PhD journey through his unconditional love, support and tolerance. I thank my friends and family members who have shown their support through calls, online chats, and emails. Thank you for making me feel that I not half a world away.

I am especially grateful to my parents, Gordana and Jovica, who have always supported me. I thank you for all of the sacrifices that you made on my behalf. This thesis is dedicated to you.

Statement of Authentication

The work presented in this thesis is, to best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

Partial data from the present research has been included in the following manuscript submitted for publication at an academic journal:

Lovcevic, I., Kalashnikova, M., & Burnham, D. (revised and resubmitted). Acoustic features of infant-directed speech to infants with hearing loss. *Journal of Speech, Language, and Hearing Research.*

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Abstract

It is estimated that approximately two out of every 1000 infants worldwide are born with unilateral or bilateral hearing loss (HL). Congenital HL, which refers to HL present at birth, has major negative effects on infants' speech and language acquisition. Although such negative effects can be mediated by early access to hearing devices and intervention, the majority of children with HL have delayed language development in comparison with their normal-hearing (NH) peers. The aim of this thesis was to provide a deeper empirical understanding of the acoustic features in infant-directed speech (IDS) to infants with HL compared to infants with NH of the same chronological and the same hearing age. Three specific objectives were set. The first objective was to investigate the effects of HL and the degree of hearing experience on the acoustic features of IDS. The second objective was to assess adjustments in IDS features across development in IDS to infants with HL as they acquire more hearing experience. The third objective was to evaluate the role of specific IDS components such as vowel hyperarticulation and exaggerated prosody in lexical processing in infants with NH from six to 18 months of age, at both neural and behavioural levels. This was achieved by conducting four experiments. The first experiment used a cross-sectional design that assessed the acoustic features in IDS to infants with HL with a specific focus on whether and how infants' chronological age and hearing age may affect these features. Experiment 2 included a longitudinal investigation that focused on the acoustic features of IDS to infants with HL and infants with NH of the same hearing age. We sought to identify how infants' changing linguistic needs may shape maternal IDS across development. Experiments 3 and 4 focused on lexical processing in six-, 10-, and 18-month-old infants, whereby we aimed to identify the role of specific IDS features in facilitating lexical processing in infants with NH at different stages of language acquisition.

The results of this thesis demonstrated that mothers adjust their IDS to infants with HL in a similar manner as in IDS to infants with NH. However, some differences are evident in the production of the corner vowels /i/ and /u/. These differences exist even when controlling for the amount of hearing experience had by infants with HL. Additionally, findings demonstrated a relation between vowel production in IDS and infants' receptive vocabulary indicating that the exaggeration in vowel production in maternal IDS may play a fostering role in infants' language acquisition. This linguistic role was confirmed as vowel hyperarticulation was also found to facilitate lexical processing at the neural level in 10-month-old infants. However, with regard to older infants (18 months), our findings demonstrated that natural IDS with heightened pitch and vowel hyperarticulation represents the richest input that facilitates infants' speech processing.

In summary, the findings of this thesis suggest that congenital HL in infants affects maternal production of vowels in IDS resulting in less clear vowel categories. This may result from mothers adjusting their vowel production according to infants' reduced vowel discrimination abilities, thus, adjusting their IDS to infants' linguistic competence. Additionally, receptive vocabulary seems not to be affected by this, indicating the role of other cues for building a lexicon in infants with HL that warrant further investigation. Furthermore, the findings suggest that pitch and vowel hyperarticulation in IDS play significant roles in facilitating lexical processing in the first two years of life.

THESIS OVERVIEW

Usually infants with normal hearing (NH) acquire their surrounding language with ease, but the majority of infants with permanent congenital hearing loss (HL) fall significantly behind compared to their NH peers in the development of receptive and expressive communication skills (Davis, 1974; Geers, Kuehn, & Moog, 1981; Levitt, McGarr, & Geffner, 1987). These delays in language development are evident from early infancy, and their consequences persist across the school years causing problems with reading and learning, often resulting in decreased academic achievement, communication problems, and social isolation.

For these reasons, it is important to determine the environmental factors that are crucial for optimal language development in children with HL, and which of these factors are potentially degraded in the speech input to infants and children with HL. One important factor is the quality of infant-directed speech (IDS) since research has shown that acoustic characteristics of IDS (of particular interest for this thesis, the hyperarticulation of vowels) are affected by sensory or cognitive impairment in the infant (Lam & Kitamura, 2010, 2012; Kalashnikova, Goswami, & Burnham, 2018). Studies have shown that mothers modify the acoustic properties of their speech according to the hearing level and linguistic abilities of their infants with HL, with or without Cochlear Implants or Hearing Aids (Bergeson, 2011; Bergeson, Miller, & McCune, 2006). Nevertheless, the extent of such changes in IDS to infants with HL and any consequent effects on children’s language development remain unknown.

The aim of this doctoral project is to investigate the role of specific features in maternal IDS and how they may be affected by HL in the infant. Within this aim the first objective is to investigate the effects of HL and the degree of hearing experience on the acoustic features of IDS. This entails identifying the strength and nature of particular components of IDS to infants with HL as compared with those in IDS to infants with NH matched by chronological or hearing age, and how these components might be the result of infants' chronological age or hearing experience. The second objective is to assess adjustments in IDS features across development in IDS to infants with HL, as they acquire more hearing experience. The third objective is to evaluate the role of specific IDS components such as vowel hyperarticulation and exaggerated prosody in lexical processing in infants from six to 18 months of age who have NH, at the neural and behavioural levels.

Results from the present thesis will shed light on the language learning mechanisms used by infants with HL and NH and reveal how these might differ, and in particular, how the presence or absence or relative strength of particular IDS components might facilitate infants' language development. In turn, conclusions will be drawn about whether the IDS that infants with HL usually hear facilitates or hinders their lexical processing and growth of vocabulary size.

Chapter 1 will present a literature review on language development and qualities of IDS in infants with NH. Chapter 2 will present a literature review on language development and qualities of IDS in infants with HL. Chapter 3 will investigate the acoustic features in IDS to infants with HL and NH, while Chapter 4 will investigate the IDS features to infants with HL and NH over development. Chapter 5 will examine the roles of pitch and vowel hyperarticulation in lexical processing in 18-month-old infants at the behavioural level, whereas Chapter 6 will assess the roles of these features in lexical processing in six- and 10-month-old infants at the neural level. Chapter 7 will present a General Discussion of the findings of the experimental studies and will discuss avenues for future research.

CHAPTER 1

Language Development in Infants with Normal Hearing

1.1 Introduction

It has been demonstrated that, in addition to intrinsic mechanisms, the linguistic input in the immediate environment plays a major role in language acquisition (Bornstein, Haynes, & Painter, 1998; Hoff, 2003; Payne, Whitehurst, & Angell, 1994). When addressing infants, adults produce a specific speech register known as infant-directed speech (IDS) (Fernald & Simon, 1984). Compared to adult-directed speech (ADS), IDS has been classified as a form of *hyper speech* that yields several positive effects on infants' early emotional and cognitive development including emotional regulation, engaging attention, and promoting language acquisition (Fernald, 2000). Studies with normal-hearing (NH) infants have shown that when listening to IDS compared to ADS, infants are more successful at segmenting individual words from fluent speech, recognising familiar words and their meaning, and learning new words (Ma, Golinkoff, Houston, & Hirsh-Pasek, 2011; Singh, Nestor, Parikh, & Yull, 2009; Thiessen, Hill, & Saffran, 2005). Such findings strongly suggest that IDS is not simply an unintended consequence of interacting with infants, but it plays an important role in their language acquisition.

Two fundamental skills in language learning are the ability to map new words to their referents and to recognise familiar words and their meanings. Although infants produce their first words only around the end of their first year of life, the process of language acquisition starts much earlier (Werker & Yeung, 2005). This thesis will focus on the processes of the recognition of familiar words and the role of IDS in these processes. Since there are skills that precede lexical processing and are crucial for it, the literature review will begin with discussing the development of speech perception (Section 1.2.1) and word segmentation abilities (Section 1.2.2) leading to word recognition (Sections 1.2.3 and 1.3.1), and conclude with an exposition of the two IDS features of particular concern in this thesis: the exaggerated prosody in IDS and the vowel hyperarticulation in IDS (Sections 1.4.1 and 1.4.2).

1.2 The First Year of Life

1.2.1 Speech perception.

1.2.1.1 Perception abilities at birth.

Infants' ability to hear the sounds of an ambient language starts in utero (Gerhardt & Abrams, 2000), and it shapes their speech perception through the first year of life paving the way for learning the sounds of their native language, its phonotactic rules, and its words. Newborn infants prefer to listen to speech than to non-speech sounds (Jusczyk, 1997; Vouloumanos & Werker, 2007), prefer to listen to the stories read by their mothers in the last few weeks of the pregnancy than to novel stories (DeCasper & Spence, 1986), and prefer their mother's voice to the voices of other females (DeCasper & Fifer, 1980). Infants' preferences for speech over non-speech and for their mother's voice may serve as powerful facilitators to direct infants' attention to crucial features of speech and thus facilitate language acquisition. Furthermore, neurophysiological studies have shown that exposure to speech in neonates activates specialised areas of the brain. For example, there is increased activity in the left hemisphere compared to the right (Dehaene-Lambertz & Pena, 2001) when presented with normal speech over speech played backward (Pena et al., 2003). Such findings indicate the availability of basic psychoacoustic and cognitive abilities necessary for speech perception at birth or shortly after birth.

1.2.1.2 Native speech perception.

In order to process and learn words, infants first must learn the phonemes of their native language. One of the most fascinating abilities of newborn infants is their ability to discriminate the phonetic contrasts that are not present in their native language (Werker & Tees, 1984). This ability, however, decreases as infants approach their first birthday whereas the ability to discriminate native contrasts increases (Aslin, 1981; Polka & Werker, 1994; Streeter, 1976; Trehub, 1976; Tsushima et al., 1994). In a seminal study, Werker and Tees (1984) found that six- and eight-month-old English-exposed infants could discriminate the Hindi retroflex-dental contrast and the Nthlakampx glottalised velar versus uvular contrast, but by 10 to 12 months of age these infants could no longer discriminate these non-native contrasts. Similarly, more recent electrophysiological evidence has shown that infants' event-related potential (ERP) responses to non-native contrasts are present at seven months but disappear by 11 months of age, along with increasing responsiveness to native language consonant contrasts (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). These studies suggest that infants can discriminate most if not all phonetic contrasts in the world's languages without specific experience, but as they accumulate more experience with their native language, their perceptual performance on non-native contrasts declines. This reorganisation of perceptual abilities occurs earlier for vowels than consonants; around four to six months for vowels (Kuhl, 1994; Kuhl, 2000; Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992; Polka & Bohn, 1996; Polka & Werker, 1994), and around eight to 10 months for consonants (Best & McRoberts, 2003; Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995; Kuhl et al., 2006; Tsushima et al., 1994; Werker, Gilbert, Humphrey, & Tees, 1981; Werker & Tees, 1983, 1984). This developmental difference could be due to vowels carrying much of the prosodic information that infants are attracted to early on (Fernald, 1992; Mehler et al., 1988). Also, during this period infants become attuned to lexical tones in their native language (Mattock & Burnham, 2006; Mattock, Molnar, Polka, &

Burnham, 2008) suggesting that this perceptual reorganisation happens along a similar timeframe for different types of phonological categories.

From these findings it can be concluded that language experience during the first year of life plays a major role in defining language-specific phonetic categories. Indeed, it has been shown that better native contrast perception at seven-and-a-half months predicts faster language growth, while better non-native contrast perception at this age predicts slower language growth (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Kuhl et al., 2008). Thus, all other things being equal, early language experience results in the development of native language speech representations which influence future language learning (Kuhl et al., 2008).

To sum up, research shows the importance of linguistic experience in the development of infants' speech perception. Infants begin life with the ability to discriminate possibly all phonetic contrasts of all the world's languages. Then over age, perceptual performance on non-native speech sounds decreases by the time infants approach their first birthday. Tuning in selectively to native speech sounds does not require reinforcement or explicit teaching; rather it depends on environmental information, specifically the linguistic input to the infant. Hence, learning of the native language phonetic categories occurs as a function of exposure to the ambient language, and the development of selective speech perception, factors that may be compromised in infants with HL.

1.2.2 Word segmentation.

Another challenge that infants must overcome in order to recognise and learn words is to identify individual words in continuous speech. This is not an easy task, since in continuous speech words are not separated by pauses as in most written text. Nevertheless, infants develop the ability to segment individual words from fluent speech between seven and 10 months of age (Jusczyk, Houston, & Newsome, 1999; Mattys & Jusczyk, 2001; Saffran, Newport, & Aslin, 1996). While adults segment continuous speech via top-down knowledge of familiar words to match parts of the speech stream and predict word boundaries (Norris, 1994), such a strategy is not available to young infants who have few if any words in their repertoire. Accordingly, infants parse the continuous speech stream into words using the cues available to them in the stimulus: prosodic markers (Jusczyk et al., 1999), phonotactic constraints (Mattys, Jusczyk, Luce, & Morgan, 1999), context-sensitive allophones (Hohne & Jusczyk, 1994), and statistical regularities in the input (Saffran et al., 1996). As soon as infants start acquiring language-specific lexical and morphosyntactic knowledge, they also start employing top-down processes. For example, they can use the few words acquired in their first months of life such as their own name or words like ‘mum’ and ‘dad’ (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005). Beyond low-level acoustic and statistical cues, other cues available to infants in this process include frequent function morphemes (Shi & Lepage, 2008), preceding determiners (Höhle & Weissenborn, 2000), and highly frequent functors (Shi, Cutler, Werker, & Cruickshank, 2006).

In order to learn word meanings, it is necessary for infants to know what qualifies as a word in their native language, and to form lexical representations that can be associated with word meanings. In addition, infants’ lexical representations must be robust to different speech variations such as accent, gender of the speaker, and different voices. Forming the lexical representations for some of the most frequent words infants hear such as “mummy”, “daddy”, and infant’ own name may help in establishing a solid word knowledge base, which can then be exploited in subsequent segmentation and recognition.

1.2.3 Word recognition in the first year of life.

One of the first words that infants are able to recognise is their own name and this occurs around four months (Mandel, Jusczyk, & Pisoni, 1995). This is not surprising since the infant’s own name is one of the most frequent and particularly important words in the infant’s environment. Similarly, word recognition can occur earlier for words that refer to the most important social figures in their life. Indeed, six-month-old infants can associate the labels "mommy" and "daddy" correctly to videos presenting their own parents (Tincoff & Jusczyk, 1999).

Beyond words referring to the infant's own name and important social figures, there is early word recognition for other word categories as well. Behavioural studies (Bergelson & Swingley, 2012, 2015; Tincoff & Jusczyk, 2012) have demonstrated that six- to nine-month-old infants can recognise words related to food and body parts. Additionally, success at word recognition at this age has been positively associated to the expressive vocabulary at 13 to 14 months of age.

In addition to behavioural data, there are also studies that offer electrophysiological evidence for early word recognition. For example, it has been shown that nine- and 10-month-old infants are able to segment and recognise familiar words in fluent speech (Kooijman, Hagoort, & Cutler, 2005; Parise & Csibra, 2012), and that word recognition at this age is not merely associative in nature, but involves referential meaning showing that infants really understand the meaning of words stored in their early lexicon (Parise & Csibra, 2012).

1.3. The second year of life

1.3.1 Lexical processing.

Lexical processing - recognition of a spoken word - is one of the fundamental skills in language acquisition and refers to the process of matching the spoken input with mental representations associated with word candidates and selecting one of these of candidates (Dahan & Magnuson, 2006). In other words, lexical processing consists of the ability to gain access to the meaning of familiar words stored in the mental lexicon. It can be measured by speed and accuracy in recognising the visual referent of a familiar word in real time (Fernald, Pinto, Swingley, Weinbergy, & McRoberts, 1998). The Looking While Listening Procedure (LWL, Fernald, 1998; Fernald, Perfors, & Marchman, 2006; Fernald, Zangl, Portillo, &

Marchman, 2008) is used to assess young infants' lexical processing by evaluating the time course of children's eye movements towards pictures or scenes while hearing sentences describing one of them (Hirsh-Pasek & Golinkoff, 1996).

Learning to recognise, understand, and produce a new word properly is a gradual process. During their second year, infants learn to recognise more and more words (Dale & Fenson, 1996), and the speed and efficiency of word recognition increases (Fernald, 2000; Fernald et al., 1998; Fernald et al., 2006; Friedrich & Friederici, 2005). In other words, they get better at recognising and interpreting the same word in more diverse and demanding contexts (Fernald, 2000; Fernald et al., 1998). Fernald et al. (2006) conducted a longitudinal investigation of receptive and expressive language skills in English-learning infants from 12 to 25 months of age. Using the LWL procedure, they investigated how the development of competence in spoken word recognition might be related to expressive vocabulary growth and the emergence of grammatical abilities. There were two major findings. First, it was found that infants gained more competence in word recognition between 15 and 25 months, which authors related not only to infants' ability to respond efficiently to an increasing number of words but also to faster and more accurate responding to the same words learnt months earlier. Second, the results indicated greater and earlier acceleration in vocabulary growth across second year of life for infants who at 25 months had displayed faster and more accurate online comprehension. These findings provided the first empirical evidence for a relation between efficiency in word recognition and rate of language learning in the same group of infants followed longitudinally.

Most importantly, studies have demonstrated the importance of lexical processing ability for later language skills. For example, speed and accuracy in lexical processing at 18 months predicts expressive vocabulary size at 30 months (Marchman et al., 2019), variation in receptive vocabulary at three years (Marchman, Adams, Loi, Fernald, & Feldman, 2015), and receptive vocabulary, global language abilities, and nonverbal intelligence quotient (IQ) at four-and-a-half years (Marchman et al., 2018). In addition, speed and accuracy of lexical processing at 25 months predicts vocabulary growth across the second year (Fernald et al, 2006), and even individual differences in language and cognitive outcomes at eight years of age (Marchman & Fernald, 2008). These findings underline the importance of lexical processing skills in infants' language and cognitive development, a central aspect of the studies with infants with NH in this thesis.

1.3.3 Word production.

During the first year, infants acquire different language skills which enable them to start producing their first words sometime between 12 and 15 months of age. By two years of age, infants produce between 100 to 600 distinct words. By six years of age, children's receptive vocabulary includes around 14000 words, while expressive vocabulary numbers a little less than 14000. This suggests that the rate of word acquisition is nine to ten words per day between two and six years of age.

Different stages in the development of word production have been proposed. The first stage is the one-word stage characterised by infants' production of single words without combining them (Dromi, 1987). The second stage includes combining two or more words into a single utterance. Even though word production begins at a similar age and progresses through similar stages for all infants, the rate at which infants produce their first words differs resulting in a great deal of variation in the age at which infants can produce 10 words (between 12 and 16 months) and then 50 words (between 17 and 22 months) (Robb, Bauer, & Tyler, 1994).

1.3.3.1 Vocabulary spurt.

Between 18 and 24 months of age, an abrupt change is observed in infant speed of word acquisition, a change known as the vocabulary spurt or naming explosion (Bloom, 1973). Two types of theories have been proposed in order to explain the vocabulary spurt. One of them has focused on endogenous, whereas the another one has focused on exogenous mechanisms.

According to the theories that propose endogenous mechanisms, the vocabulary spurt is related to representational and/or maturational changes in the infant's brain, such as the naming insight or understanding that words refer to things and/or that things have names (Dore, Franklin, Miller, & Ramer, 1976; Reznick & Goldfield, 1992). Alternatively, the vocabulary spurt occurs when object concepts and categories become more detailed and refined (Gopnik & Meltzoff, 1987; Nazzi & Bertoncini, 2003). Other theories have proposed different endogenous mechanisms related to linguistic refinements such as word segmentation (Plunkett, 1993), word retrieval capacities (Dapretto & Bjork, 2000), or hemispheric specialisation development (Mills, Coffey-Corina, & Neville, 1993). These theories assume that the vocabulary spurt results from endogenous changes in the infant. A contrasting hypothesis was introduced by McMurray (2007). He argued that (i) words are acquired in parallel, and (ii) some words are easier to acquire than other words, such that the vocabulary spurt is imminent. This distribution in difficulty stems from different factors, including frequency, phonology, syntax, the infant's competences, and the contexts in which words occur. This hypothesis assumes that the vocabulary spurt is the result of exogenous factors such as frequency of word usage. However, it is possible that a combination of both endogenous and exogenous factors contributes to the vocabulary spurt resulting in increased efficiency in word recognition and faster rate of word learning, representing an important developmental milestone in language acquisition (Fernald, 2000).

1.4 Infant-directed speech

In the last 20 years or so, many studies have focused on the role of infant-directed speech (IDS) in language development. IDS refers to the style of speaking used in interactions with infants. In comparison to ADS, IDS has longer vowels and pauses (Andruski & Kuhl, 1997), increased repetition and slower rate (Fernald & Simon, 1984), greater variations in fundamental frequency (McRoberts & Best, 1997), a high proportion of questions (Soderstrom, Blossom, Foygel, & Morgan, 2008), and exaggerated articulation of speech sounds (Burnham, Kitamura, & Vollmer-Conna, 2002; Kuhl et al., 1997). In addition, in the visual modality, facial movements made while producing IDS differ from those in ADS (Chong, Werker, Russell, & Carroll, 2003; Shepard, Spence, & Sasson, 2012) with characteristics such as exaggerated lip movements (Green, Nip, Wilson, Mefferd, & Yunusova, 2010), exaggerated smiles, increased eyebrow raising, and widened eyes (Werker & McLeod, 1989). Since it is difficult to reproduce IDS features in the absence of an infant (Fernald & Simon, 1984), it has been argued that the production of IDS is a reflexive, instinctive, and unconscious speech behaviour that parents and others produce when speaking to an infant (Papoušek, Bornstein, Nuzzo, Papoušek, & Symmes, 1990). It has been demonstrated that infants prefer to listen to IDS over ADS in their native (Cooper & Aslin, 1990; Fernald, 1985) and also in a foreign language (Fernald & Morikawa, 1993; Werker, Pegg, & McLeod, 1994).

The quantity of speech in the infant's environment for language development has been shown to be important (Hart & Risley, 1995), but it must be noted that the critical factor is the speech addressed directly to the infant (IDS). Accordingly, it has been shown that children who are exposed to more speech input and more diverse vocabulary exhibit stronger vocabulary growth (Hoff & Naigles, 2002; Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991). Also, infants who are exposed to a greater quantity of IDS at 18 to 19 months of age demonstrated faster lexical processing skills and greater expressive vocabulary at 24 months of age (Hurtado, Marchman, & Fernald, 2008; Weislander & Fernald, 2013). On the other hand, speech overheard by infants has not been found to have beneficial effects on infants' lexical processing and vocabulary development (Weislander & Fernald, 2013). These findings show that speech input that infants receive in their everyday lives plays an important role in their language acquisition.

In conclusion, the quantity of IDS input is an important factor in infant language acquisition. The review now turns to the quality of IDS, the primary focus of this thesis. The focus will be on the acoustic features of IDS and the potential role that these features may play in infant language development.

1.4.1 Prosodic qualities of IDS.

It is now well-established that compared to ADS, IDS is characterised by exaggerated prosody: greater pitch height, wider pitch range, distinctive pitch contours, slower speech rate, and longer pauses in comparison to ADS (Bergeson & Trehub, 2002; Fernald, 1992; Fernald & Simon, 1984; Fernald et al., 1989; Trainor, Austin, & Desjardins, 2000; van de Weijer, 1997). These prosodic modifications in IDS have been found across various world languages including Indo-European languages such as English, French, Italian, and German (Fernald, 1989), tonal languages such as Mandarin (Grieser & Kuhl, 1988), Cantonese (Rattanasone, Burnham, & Reilly, 2013), Thai (Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin, 2002), and pitch-accented languages such as Japanese (Fernald, 1989). These findings suggest that exaggerated prosody in IDS is universal, but there are some variations. For example, higher pitch is absent in IDS of Quiche-speaking mothers (Bernstein Ratner & Pye, 1984), possibly because high pitch is reserved for addressing social superiors in their culture. Nevertheless, even though some differences exist, the majority of studies have demonstrated a presence of exaggerated prosody in IDS (Cristia, 2013; Wang, Houston, & Seidl, 2019).

This thesis focuses on the exaggeration and variability in pitch production in IDS. Pitch is the perceptual correlate of fundamental frequency (F0) that represents the rate of vibrations of the vocal cords within the larynx (Atkinson, 1973). Pitch features can be grouped into three main categories: mean pitch height; pitch range - the variations and excursions of pitch within and between utterances; and pitch contour - the overall shape of pitch variations over time, operationalised as pitch direction (rising, falling, flat; see Figure 1 for an example). A range of evidence demonstrates that F0- or pitch-related exaggerated features are more commonly observed in IDS compared to ADS. Thus, F0 mean values are higher in IDS compared to ADS

(Fernald & Simon, 1984; Grieser & Kuhl, 1988); F0 variations are much wider and smoother in typical IDS giving IDS its typical exaggerated modulation (Fernald & Mazzie, 1991; Fernald & Simon, 1984); and F0 contours, such as rising, falling and sinusoidal-bell shaped are more commonly observed in IDS, whereas flat pitch productions are more prevalent in ADS (Fernald & Simon, 1984; Knoll & Costall, 2015).

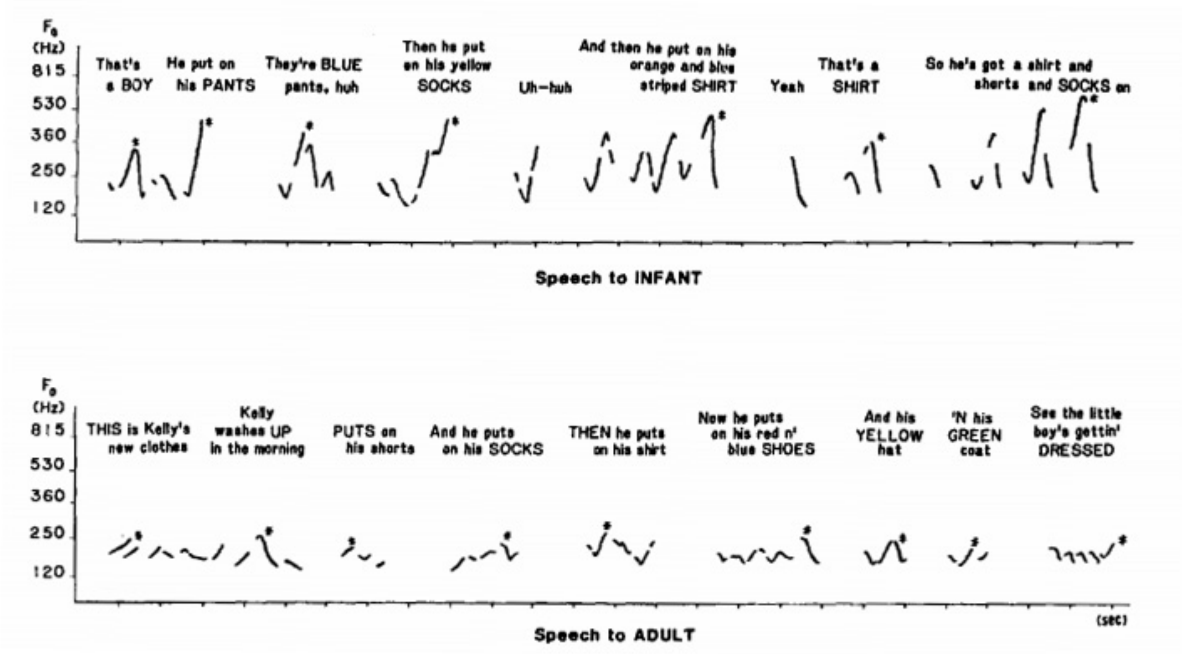

Figure 1. Examples of F0 contours in the speech of one mother describing the picture book to her infant and to an adult (Figure from Fernald, A., & Mazzie, C. (1991). Prosody and focus in speech to infants and adults. *Developmental psychology*, *27*(2), 209.).

1.4.1.1 IDS prosody and affect regulation.

Although research suggests that IDS plays a role in eliciting and regulating infant emotions (Fernald, 1991; Papoušek, 1992; Santesso, Schmidt, & Trainor, 2007; Singh, Morgan, & Best, 2002; Trainor et al., 2000), to date, there are few studies that have investigated the role that exaggerated pitch plays in emotion regulation. The few published studies in this area have found positive associations between pitch exaggerations in IDS and infants' affect. For example, infants respond with more positive affect to IDS with exaggerated pitch height and wider pitch range (Fernald, 1993), and demonstrate more smiling and gaze directed to the mother (Stern, Spieker, Barnett, & MacKain, 1983). Moreover, a recent study suggests that wider pitch range in IDS is related to decreasing infant' negative affect in three-month-olds, but only in cases where mothers have high maternal sensitivity (Spinelli & Mesman, 2018). Additionally, Kitamura and Burnham (2003) demonstrated that pitch adjustments in IDS are related to maternal communicative intentions with pitch height adjustment being used to produce affective utterances, and adjustment in pitch range used to produce directive utterances. Thus, pitch modifications in IDS play an important role in early affect regulation of the young infant and in the transmission of maternal emotional and communicative intent.

1.4.1.2 IDS prosody and attention.

It has been proposed that exaggerated pitch in IDS aids language acquisition by attracting and maintaining infants' attention to the speech stream (Cooper & Aslin, 1990; Fernald & Simon, 1984). Indeed, exaggerated pitch height and pitch range have been shown to lead to increased attention to the speech stream in pre-term neonates and in six- to eight-month-old infants (Butler, O'Sullivan, Shah, & Berthier, 2014). Additionally, six-month-old infants show gaze-following behaviours in response to IDS but not to ADS prosody (Senju & Csibra, 2008). Furthermore, variability in pitch production in IDS to six-month-old infants has been related to infants' joint attention at 12-months of age, suggesting possible long-term effects of exaggerated pitch in IDS on infants' attention development. Increased attention to the speech stream may affect language learning by increasing infants' arousal and priming their system for learning (Kaplan, Jung, Ryther, & Zarlengo-Strouse, 1996). Indeed, it has been demonstrated that pitch exaggeration in IDS predicts infants' associative learning (Kaplan, Bachorowski, & Zarlengo-Strouse, 1999). Overall, these findings indicate that pitch modifications in IDS play an important attentional role in infancy that in turn can facilitate infant learning via associative mechanisms.

1.4.1.3 IDS prosody and infant linguistic outcomes.

A number of studies have considered the effects of IDS prosody on enhancing speech processing, by comparing infants' performance on linguistic tasks that use stimuli with IDS versus ADS prosody. Thiessen and colleagues (2005) assessed seven-month-old infants' segmentation of words and part-words presented in IDS and ADS and found successful segmentation only in infants exposed to IDS. Since both IDS and ADS provided statistical cues to the word boundaries, and the only difference between the speech registers was in prosodic features, these findings indicate that IDS prosody facilitates infants' word segmentation. In another study, Trainor and Desjardins (2002) showed that the pitch contours of IDS facilitate infants' performance on a vowel discrimination task at six and seven months, the age at which infants are beginning to tune into native language vowel categories. In contrast, their findings also demonstrated that exaggerated pitch height of IDS failed to facilitate infants' vowel discrimination. Together, these studies suggest that exaggerated prosody in IDS promotes speech processing skills during the first year, supporting the importance of IDS prosody during the early stages of language acquisition.

Additionally, there is evidence that the exaggerated prosody of IDS plays a facilitative role in speech processing skills during the second year of life. Specifically, exaggerated prosody of IDS evident in greater pitch height, wider pitch range, and slower duration has been found to facilitate 17- and 21-month-old infants' word learning (Graf Estes & Hurley, 2013; Ma et al., 2011). These findings suggest that IDS prosody plays a role not only in speech processing skills in pre-verbal infants but also in infants on the verge of the vocabulary spurt and in older infants who have more developed vocabularies. However, these results must be treated with caution given that Song, Demuth, and Morgan (2010) failed to find any facilitative effect of pitch range on 19-month-olds' lexical processing. Regarding the long-term effects of exaggerated pitch in IDS on infants' language skills, greater pitch variability produced by mothers in IDS to three-month-olds was associated with a larger productive vocabulary in these infants at 12 months (Porritt, Zinser, Bachorowski, & Kaplan, 2014). And, in complementary results, the presence of flat and less varied pitch contours has been found in maternal IDS to 20-month-old late-talking infants, infants who have not yet acquired a 50-word vocabulary as compared to IDS directed to typically developing infants suggesting that maternal input may contribute to the delay in language acquisition (D'Odorico & Jacob, 2006). In contrast, other studies have found no correlation between prosodic features of IDS and 15-month-old infants' performance on a word recognition task (Suttora et al., 2017). Together, these findings provide a mixed picture of the role of prosody in infants' language acquisition. Results are inconsistent with some showing a facilitative effect of IDS prosody and others failing to find any such facilitation. It is possible that the facilitative effect of IDS prosody depends on the infants' age and the specific linguistic needs associated with that age.

1.4.2 Segmental qualities of IDS.

With regard to the segmental qualities of IDS, research has shown that vowels and consonants are exaggerated in IDS compared to ADS. One of the features that can be exaggerated in consonants is voice onset time (VOT). VOT refers to the interval between the release of stop occlusion and the onset of vibration of the vocal folds, a cue which differentiates voiced and voiceless stop consonants (Abramson & Lisker, 1970; Zlatin, 1974). Previous studies of VOT in IDS have led to different conclusions. While studies with three- and seven-month-old infants found shorter VOT in IDS than in ADS (Sundberg & Lacerda, 1999; Synnestvedt, Bernstein Ratner, & Newman, 2010), studies with infants between 11 and 14 months of age found longer VOT in IDS than in ADS (Sundberg, 2001; Synnestvedt et al., 2010). Thus, it appears that for some, yet unknown reason, once infants are older and approaching their first speech productions, mothers increase VOT duration in comparison with the pre-verbal stage. Regarding other features that differentiate consonantal categories, it has been demonstrated that there are more pronounced differences between /s/ and /ʃ/ in IDS as compared to ADS (Cristia, 2010), and more canonical variants for word-final alveolar stops in IDS compared to ADS (Dilley, Millett, McAuley, & Bergeson, 2014). With regard to vowels, the main segmental modifications of vowels in IDS are in regard to vowel hyperarticulation. This feature is the focus of this thesis, and it is discussed in the next section.

1.4.2.1 Vowel hyperarticulation.

Vowel hyperarticulation, the acoustic exaggeration of vowel categories, refers to the increase of the area encompassed by the three corner vowels /i, u, a/ in IDS compared to ADS (Kuhl et al., 1997). It is indexed by plotting these three vowels in two-dimensional Formant 1 / Formant 2 (F1/F2) space and calculating the area of the resulting triangle (see Figure 2 for an example of vowel triangles in IDS and ADS). This measure of vowel hyperarticulation was devised by Kuhl and colleagues (1997), and it has been used in the majority of studies on vowel hyperarticulation in IDS. In this case, the expected larger vowel triangle area in IDS compared to ADS is interpreted as separation of vowel categories in IDS making them more discriminable.

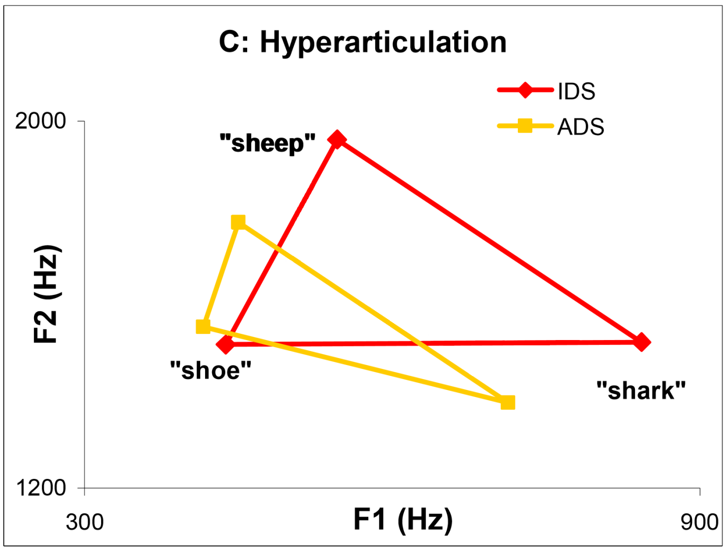

Figure 2. Vowel hyperarticulation (in Formant 1/ Formant 2 vowel space) in IDS and ADS (Figure from Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2002). What's new, pussycat? On talking to babies and animals. *Science, 296*(5572), 1435-1435.).

CHAPTER 1: LANGUAGE DEVELOPMENT IN INFANTS WITH NH

In their seminal study, Kuhl and colleagues (1997) demonstrated the presence of vowel hyperarticulation in IDS compared with ADS in productions by American English, Russian and Swedish mothers. These three languages were chosen since they have distinctively different vowel systems: Russian has five vowels, American English nine, and Swedish 16 vowels. Although these languages have different vowel systems, the point vowels /a, i, u/ occur in each of them (and in the majority of world languages, Ladefoged & Maddieson, 1996). In the Kuhl et al. (1997) study, mothers of two- to five-month-old infants were recorded while speaking to their infant (IDS) and while speaking to an adult experimenter (ADS). In order to obtain maternal production of the three point vowels, the mothers were provided with three toys which names contained each of the vowels. Results showed that mothers in each of the three languages produced a larger vowel space in IDS compared to ADS.

Later studies have demonstrated the presence of vowel hyperarticulation in IDS in American English (Adriaans & Swingley, 2017; Cristia & Seidl, 2014), British English (Lorge & Katsos, 2019), Australian English (Burnham, et al., 2002; Kalashnikova & Burnham, 2018; Kalashnikova, Carignan, & Burnham, 2017; Kalashnikova et al., 2018; Lam & Kitamura, 2010, 2012; Xu, Burnham, Kitamura, & Vollmer Conna, 2013), Mandarin Chinese (Liu, Kuhl, & Tsao, 2003; Tang, Xu Rattanasone, Yuen, & Demuth, 2017), and Japanese (Miyazawa, Shinya, Martin, Kikuchi, & Mazuka, 2017). The majority of these studies used the same data elicitation and analysis method as Kuhl and colleagues (1997): three toys which names contained the point vowels /a, i, u/ in order to elicit these vowels as well as the same formula to calculate the vowel space triangles in both IDS and ADS. In this thesis, these conventions regarding stimulus items to elicit the point vowels and the methods for deriving the dependent variables will also be used.

1.4.2.3 Vowel hyperarticulation in other speech registers.

Research on other speech registers suggests that vowel hyperarticulation is also present depending on the needs of the audience; vowels in speech directed to foreigners (Lorge & Katsos, 2019; Uther, Knoll, & Burnham, 2007) and computers (Burnham, Joeffry, & Rice, 2010) are hyperarticulated, but not in speech directed to pets (Burnham et al., 2002), unless that pet is a parrot, a bird capable of some approximation of human speech (Xu et al., 2013). Aside from linguistic competence, the speakers themselves are also sensitive to listeners' linguistic processing needs. For example, vowel hyperarticulation is found in speech directed to adults with HL (Ferguson & Kewley-Port, 2002, 2007; Hazan & Baker, 2011), in speech produced with Lombard effect (Castellanos, Benedí, & Casacuberta, 1996), in speech via a three-channel noise vocoder, and in speech with simultaneous babble noise (Hazan & Baker, 2011). It could be that in these speech contexts, speakers receive cues via covert or even via direct feedback from their listeners, or that speakers unconsciously adjust their speech through the process of phonetic convergence or accommodation (Pardo, 2006).

Similar adjustments to vowel hyperarticulation have been observed in IDS to infants who are affected by deficits in auditory processing (Kalashnikova et al., 2018), or who have hearing difficulties (Lam & Kitamura, 2010; Wieland, Burnham, Kondaurova, & Dilley 2015). Kalashnikova and colleagues (2018) examined IDS of mothers with and without dyslexia to infants who are at family risk for dyslexia and to infants who are not at family risk for dyslexia. Their results demonstrated that mothers do not hyperarticulate vowels in IDS to nine- and 11-month-old infants at risk for dyslexia regardless of whether the mother herself is dyslexic or not. This suggests that in case of deficits in auditory processing, mothers attune to their infants' needs and adjust their speech accordingly. Lam and Kitamura (2012) investigated how infants' ability to hear their mother impacts vowel hyperarticulation in mothers' IDS. In their study, mothers and their infants sat in separate rooms and interacted via a double video set-up, via which the audibility of mothers' speech to infants was manipulated to half volume and entirely muted. In addition, in one half of the session mothers knew that the audibility of their voice had been attuned and in the other half they did not know. Results showed that the area of the vowel triangle in IDS decreased as the audibility of mothers' speech to infants decreased, regardless of whether mothers knew that infants could hear them or not. Indeed, in the completely inaudible condition the vowel triangle area was equal in ADS and in IDS. The authors concluded that vowel hyperarticulation in IDS is determined by feedback from the infant. Therefore, it appears that mothers adjust their production of vowels almost instantaneously when infants with NH cannot hear them. Thus, it appears that caregivers' speech may be sensitive to their infants' ability to process speech.

1.4.2.4 The role of vowel hyperarticulation in language acquisition.

It has been proposed that vowel hyperarticulation in IDS is a didactic device that facilitates infants' language acquisition. In support of this linguistic function of vowel hyperarticulation in IDS, it has been shown that infants are successful in a number of language processing tasks when stimuli are presented in IDS with hyperarticulated vowels compared to ADS. For example, vowel hyperarticulation in IDS has been shown to significantly promote infants' efficiency in spoken language processing (Song et al., 2010), vowel perception (Peter, Kalashnikova, Santos, & Burnham, 2016) and discrimination (Zhang et al., 2011). Furthermore, at the individual level, vowel hyperarticulation in maternal speech has been specifically linked to the development of infants' individual speech perception and lexical skills. For instance, Liu and colleagues (2003) showed a significant positive correlation between the size of the vowel space area in mothers' IDS and infants' performance on an independent speech perception task. More recently, Kalashnikova and Burnham (2018) demonstrated that the degree of vowel hyperarticulation in maternal IDS from nine to 19 months was a significant predictor of infants' expressive vocabulary at 15 and 19 months of age (see also Hartman, Bernstein Ratner, & Newman, 2017). Therefore, IDS with its hyperarticulated vowels, does not only attract infants' attention to speech and facilitate performance in language processing tasks, but it also appears to provide infants with the type of linguistic input that facilitates the development of their speech perception and vocabulary abilities.

1.4.2.5 Criticism of the linguistic role of vowel hyperarticulation.

Recently, literature has also emerged offering contradictory findings and explanations about vowel hyperarticulation in IDS. Specifically, a *lack* of vowel hyperarticulation in IDS has been documented for several languages including Dutch, Norwegian, Japanese, and Cantonese (Benders, 2013; Bohn, 2013; Dodane & Al-Tamimi, 2007; Englund, 2018; Martin et al., 2015; Wong & Ng, 2018). Accordingly, it has been suggested that vowel hyperarticulation is a by-product of other acoustic features of IDS, and that it does not serve any dedicated role in early language development. Importantly, even in the cases in which the vowel space has been found to be expanded in IDS, it has been noted that IDS is also characterised by greater variability in vowel production. Greater vowel variability in IDS results in phonetic categories with more variable distributions compared to ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray, Kovack-Lesh, Goodwin, & McEchron, 2013), and leads to greater possible overlap in vowel categories, thus complicating the acquisition of these vowels. This evidence challenges the claim that vowel space expansion in IDS, i.e., vowel hyperarticulation, reflects parents' implicit intention to facilitate their infants' language acquisition and the dedicated linguistic role of IDS in early language development (Cristia, 2013).

1.4.2.6 Variability in vowel production in IDS.

The effects of IDS containing high vowel variability on infants' language development are not fully understood, and it is difficult to reconcile existing findings given that they are based on different definitions and measures of vowel variability. Bradlow, Torretta, and Pisoni

(1996) devised the *vowel space dispersion* measure, which captures the distance between a central point in the speaker's vowel space and each token of a vowel. This measure captures the overall expansion or compression of individual speakers' vowel tokens and allows the detection of fine-grained individual differences in acoustic-phonetic characteristics. Using this measure, greater vowel space dispersion indicates clearer vowels and captures a different aspect of the adjustment to vowel production that parents may produce in IDS than the vowel hyperarticulation measure (Kuhl et al., 1997). Thus, it provides a measure of vowel clarity and within-category variability.

Another measure of vowel variability involves computing the standard deviations separately for F1 and F2 frequencies for each of the three corner vowels /a, i, u/ for IDS and ADS. The presence of greater standard deviation values for F1 in IDS compared to ADS would indicate less clear vowels in terms of vowel height, and greater standard deviation values for F2 in IDS compared to ADS would indicate less clear vowels in terms of vowel backness. Previous studies using this measure have found greater vowel variability in IDS compared to ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). This greater variability has been shown to result in overlapping vowel categories, which are thought to complicate infants' acquisition of vowels in their native language (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013).

In this thesis, a comprehensive approach has been taken by using both the above measures of vowel variability and also adding one more measure that captures the distances between F1 and F2 for each of the corner vowels /a, i, u/ (Chapters 3 and 4). Each of these vowels represents an extreme point in Australian English vowel space. Acoustically they are characterised by extreme F2-F1 distances: /i/ is characterised by a wide separation between F1 and F2, whereas /a/ and /u/ are characterised by very close F1 and F2 frequencies. Hence, the F2-F1 distances for these corner vowels provide an indication of the extreme locations in the F1 by F2 space for these vowels (Gerstman, 1968). As Bradlow and colleagues (1996) pointed out, these are measures of variability in vowel production that are correlated with overall speech intelligibility.

1.4.2.7 Vowel space expansion as a by-product of other features in speech.

Findings that vowel hyperarticulation is not universally present across all language systems lead to the hypothesis that vowel hyperarticulation does not play a didactic role in language acquisition. Furthermore, it has been proposed that vowel hyperarticulation is not an acoustic feature of IDS that serves a specific role, but rather that it is simply a by-product of other IDS features. Two such sources have been proposed as factors influencing the presence of vowel hyperarticulation: speech prosody (McMurray et al., 2013) and affect (Benders, 2013). According to the prosody view, vowel hyperarticulation is a by-product of exaggerated prosodic features in IDS such as slower speech rate, wider pitch range, and shorter utterances in IDS compared to ADS (McMurray et al., 2013). Secondly, according to the affect view, vowel hyperarticulation in IDS is the consequence of greater positive affect (Benders, 2013) due to positive affect being expressed by raising the frequencies of the first three formants. Following the frequency-size relationship, high frequency speech implies a small body size signalling a lower threat level (Ohala, 1980, 1984). A study of the production of Dutch /i/, /a:/, /ɑ/, and /u/ demonstrated that each vowel had a higher F2 and F3 in IDS compared to ADS (Benders, 2013). Also, results from other studies are consistent with formant raising in IDS: greater F1, F2 for Australian English /a/ and /i/ (Burnham et al., 2002; Kalashnikova et al., 2017; Xu et al., 2013) and greater F1, F2 for Norwegian /u/ and /a:/ (Englund & Behne, 2005). These findings regarding vowel hyperarticulation and vowel dispersion in IDS call for the inclusion of different measures of assessing the exaggeration and variability in vowel production in IDS in order to obtain a comprehensive picture of vowel production. In this thesis, both vowel hyperarticulation and vowel space dispersion are used as dependent variables for both IDS and ADS.

1.4.3 Preference for IDS across development.

Although previous studies have demonstrated infants' preference for IDS over ADS in their native (Cooper & Aslin, 1990; Fernald, 1985) and also in a foreign language (Fernald & Morikawa, 1993; Werker et al., 1994), evidence suggests that this general preference for IDS changes across infant age specifically from around six months to 12 months (Cristia, 2013; Hayashi, Tamekawa, & Kiritani, 2001; Newman & Hussain, 2006; Saint-Georges et al., 2013). However, this pattern is not consistent. Using a combination of longitudinal and cross-sectional designs, Hayashi and colleagues (2001) demonstrated a U-shape developmental shift in preference for IDS over ADS in Japanese-learning monolingual infants. Their results revealed three stages in infants' preference for IDS: (i) greater preference for IDS over ADS in infants between four and six months; (ii) no preference for IDS over ADS in infants between seven and nine months; (iii) greater preference for IDS over ADS in 10- to 14-month-old infants. Newman and Hussain (2006) confirmed the preference for IDS in five-month-old American English learning infants, and no preference for IDS in nine-month-olds. These inconsistent findings may result from differences in languages or in stimuli: Hayashi et al. (2001) used natural recordings of maternal IDS recorded while mothers interacted with their infants, whereas Newman and Hussain (2006) used recordings of a speaker acting like she was speaking to an infant. Regarding the second year of life, findings are also inconsistent. While Newman and Hussain (2006) found no preference for IDS over ADS in 13-month-olds, Segal and Newman (2015) demonstrated preference for IDS over ADS in 12- and 16-month-old infants. These findings demonstrated that there are developmental changes in infants' preference for IDS which may stem from differences in developmental needs at each particular stage.

More specifically, it has been demonstrated that infants' preferences for specific IDS features change across age. Kitamura and Notley (2009) found that six-month-old infants prefer stretched vowels, while 10-month-olds prefer vowels of normal duration. Also, it has been found that four-month-old infants prefer IDS with slow tempo and high positive affect, while eight-month-olds prefer IDS with normal tempo regardless of affect (Panneton, Kitamura, Mattock, & Burnham, 2006). These differences in infants' preference for specific IDS features may result from their emerging developmental needs. For example, attunement to the vowel system of the native language could lead to an early preference for stretched vowels, which wanes at 10 months because phonological attunement has taken place (Best et al., 1995; Best & McRoberts, 2003; Kuhl et al., 2006; Tsushima et al., 1994; Werker et al., 1981; Werker & Tees, 1983, 1984). Additionally, McRoberts, McDonough, and Lakusta (2009) demonstrated that from six months of age, lexical repetition in IDS drives infants' preferences suggesting that the transition from preference to prosodic and affective features to linguistic features is driven by developmental needs. However, Segal and Newman note that the IDS preference at 12- and 16-months was due prosodic features of IDS and not to structural changes such as repetition and shorter utterances. It could be that even during infants' second year of life, IDS prosody still plays an important role in attracting attention to speech, with possible consequences for their later language acquisition.

1.4.4 Pitch and vowel hyperarticulation in IDS across development.

Two of the most distinctive components of IDS are elevated pitch and vowel hyperarticulation, and these will be investigated in this thesis with respect to lexical processing in infants with NH and infants with HL. A summary of previous relevant findings for infants with NH is presented next, and Chapter 2, Section 2.4.2 provides a summary of the findings for infants with HL.

Previous investigations propose age-related changes to the acoustic features of IDS. With regard to pitch, earlier evidence suggested greater pitch height and pitch range in IDS to four-month-olds compared to neonates and 12-month-olds (Stern et al., 1983), with a decrease between 16 and 30 months (Remick, 1976; Stern et al., 1983). In Australian English, heightened pitch has been found at six and 12 months and lower pitch height and greater pitch range at nine months (Kitamura & Burnham, 2003; Kitamura et al., 2001). On the other hand, in Thai IDS, there is greater pitch height at nine months with a decrease at 12 months (Kitamura et al., 2001). Different patterns of pitch adjustment in IDS have been found in Dutch IDS with greater pitch to 15-month-old compared to 11-month-old infants (Benders, 2013). These adjustments in pitch height across ages may be explained by different infants' needs at specific ages and maternal usage of different acoustic cues in IDS to fulfill those needs. Thus, greater pitch height at six and 12 months may be used to comfort the infant or to encourage attention, while lower pitch height at nine months may be a result of attempts to direct infants' behaviour (Kitamura & Burnham, 2003).

With regards to vowel production, there is no clear evidence that the degree of vowel hyperarticulation in maternal speech changes as a function of infants' age. Earlier accounts proposed that vowel hyperarticulation is present in IDS to infants with more advanced expressive language skills (Bernstein Ratner, 1984), but more recent studies have found evidence for vowel hyperarticulation in IDS to infants from two to 20 months of age with no differences in this feature across the ages (D. Burnham et al., 2002; E. Burnham et al., 2015; Cristia & Seidl, 2014; Kalashnikova & Burnham, 2018; Kuhl et al., 1997).

Apart from adjustments present in IDS as a function of infant age, recent evidence suggests modifications of IDS as a function of infants' linguistic and processing needs. As discussed earlier, mothers do not hyperarticulate vowels in IDS to nine- and 11-month-old infants at risk for dyslexia (Kalashnikova et al., 2018). As this adjustment was not related to whether mothers themselves were dyslexic, it appears that this adjustment in IDS resulted from infants communicating by some means their linguistic needs to the speaker. Additionally, it has been demonstrated that mothers produced greater pitch height and wider pitch range in IDS to 12- and 18-month-old infants at risk for Autism spectrum disorder compared to IDS to infants who are not at-risk (Quigley, McNally, & Lawson, 2016). It is possible that mothers of at-risk infants have a greater need to attract infants' attention to their speech and thus raise their pitch even higher than in typical IDS. These findings also align with studies investigating IDS properties to infants with HL (Bergeson et al., 2006; Kondaurova & Bergeson, 2011), which will be discussed in detail in Chapter 2. Therefore, mothers appear to adjust their IDS according to infants' developmental and linguistic needs exhibiting greater pitch and wider pitch range when infants' need attention to speech or comfort and adjusting structural features of speech when infants need more linguistic prompts.

In this thesis, the role of pitch modulation and vowel hyperarticulation in speech to infants with HL and NH will be investigated. This Chapter has set out the current state of knowledge of pitch modulation and vowel hyperarticulation in IDS to infants with NH. In Chapter 2, the focus turns to infants with HL.

CHAPTER 2

Language Development in Infants with Hearing Loss

2.1 Introduction

Approximately two out of every 1000 infants worldwide are born with unilateral or bilateral hearing loss (HL) (van Wieringen, Boudewyns, Sangen, Wouters, & Desloovere, 2018). Congenital HL, which refers to HL present at birth, has major negative effects on children's early development and later quality of life including speech and language acquisition, literacy, mental health, social and cognitive functioning, as well as academic achievement (Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007; Qi & Mitchell, 2011; Wake, Hughes, Collins, & Poulakis, 2004). These negative effects can be mediated by early access to hearing devices and intervention, which is possible as a result of newborn hearing screening programmes. With the introduction of the Universal Newborn Hearing Screening (UNHS) programme in the year 2000 in Australia, where research for this thesis was conducted, HL is detected at birth and three in every 1000 children are fitted with Hearing Aids or Cochlear Implants before entering school (Australian Hearing, 2011). Early detection and intervention yield long-term benefits such as better preschool spoken language abilities (Moeller, 2000; Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998), but even in these cases, the majority of children with HL have delayed language development in comparison with their normal-hearing (NH) peers (Moeller et al., 2007a, 2007b; Vohr, et al., 2008). This Chapter describes language development in infants with HL, with a particular focus on the role of infant-directed speech in that development (Section 2.4). Before proceeding to the language development of infants with HL, detection and intervention of HL in infants is described (Sections 2.2 and 2.3 respectively).

2.2 Detection of hearing loss in infancy

2.2.1 Newborn Hearing Screening.

The Universal Newborn Hearing Screening (UNHS) programme in Australia began in five maternity hospitals in Perth (Western Australia) in 2000 (Coates & Gifkins, 2003). Today, UNHS is conducted on regular basis in each Australian state and territory. The implementation of hearing screening at birth has led to a decrease in the age of diagnosis of HL. In 1989, before the introduction of newborn hearing screening the average age of HL detection was 20.3 months. This has now been reduced to eight months. Such early diagnosis is important since intervention can begin early in life, thus increasing the chances for optimal auditory and language development despite the HL.

There are two main procedures for conducting the hearing screening. These are an automated auditory brain stem response (AABR) and an otoacoustic emissions test (OAE). The AABR procedure consists of covering the infant's ears with ear couplers that emit a series of soft clicking sounds and placing three sensors on the infant's neck, shoulder and forehead that measure the auditory nerve (8^{th} cranial nerve) activity in response to the sound. In the OAE procedure, miniature earphones and a microphone are placed in the infant's ears, and sounds are played. If the infant can hear normally, an echo is reflected back into the ear canal and is measured by the microphone, while for an infant with HL no echo is recorded. Both procedures obtain hearing measures automatically providing a "pass" or "refer" result (Coates & Gifkins, 2003). A "refer" result indicates that the infant requires a comprehensive audiological assessment to detect whether the hearing is impaired, in which case the infant may need to commence early intervention or use an amplification device (see Figure 3 for an illustration of the detailed screening pathway).

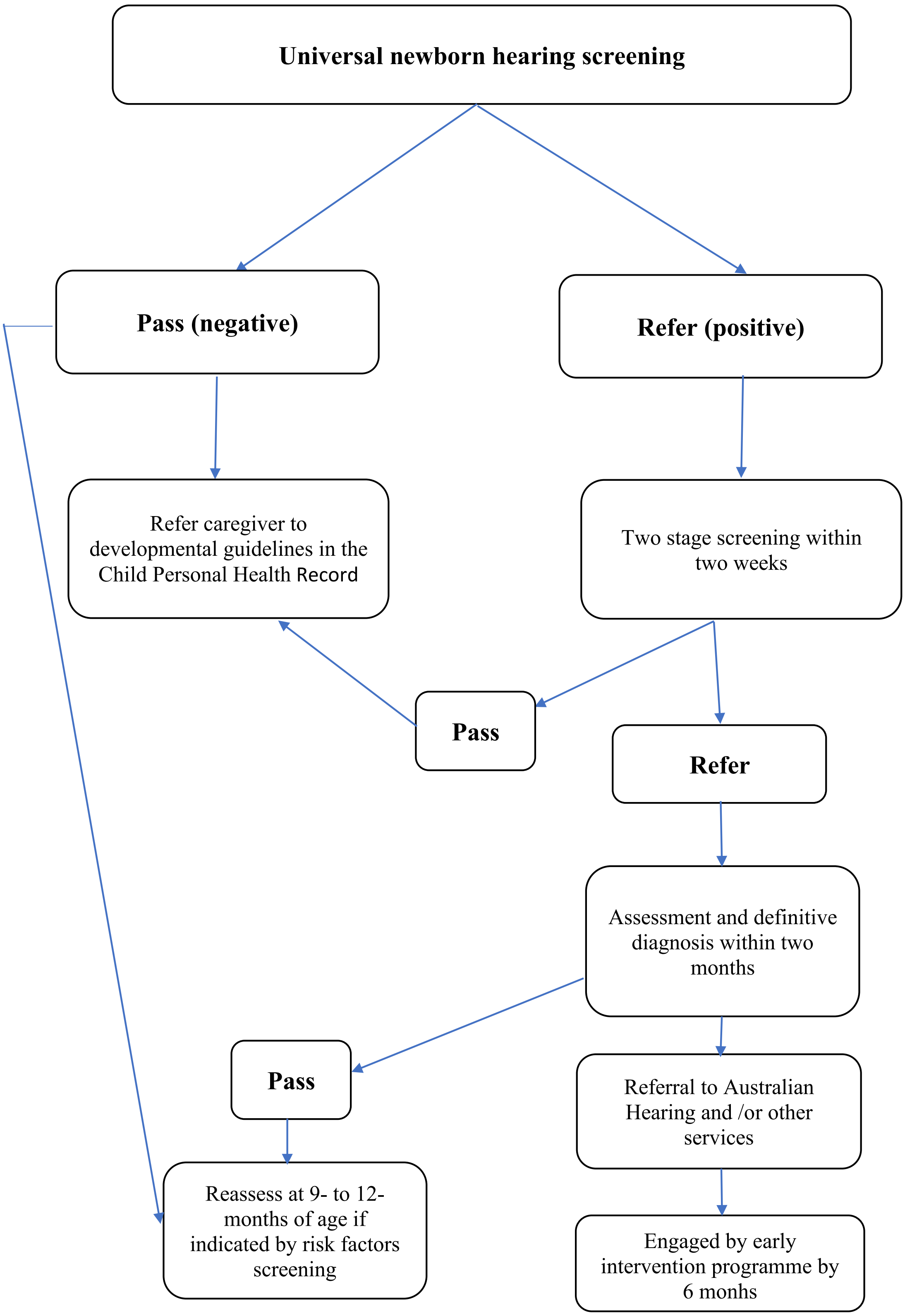

Figure 3. Detailed hearing screening pathway in Australia as proposed by National Framework for Neonatal Hearing Screening.

2.2.2 Assessment of hearing loss in infancy.

Behavioural tests are used to assess hearing in infants whose newborn screening test results in “refer”. For infants under six months of age, the Behavioural Observation Audiometry (BOA) test is used. This measures infants’ response to different environmental sounds. The test is conducted by an audiologist who produces low, mid, and high frequency sounds using different noisemakers such as crunching cellophane, bells, bicycle horns, and rattles. Possible infant responses include trying to look to the sound, startling, stirring from sleep, or stopping sucking. Although this procedure provides information about the severity of HL and the infant’s ability to detect different sound frequencies, the exact hearing level cannot be determined. Thus, once infants develop head control and can localise sounds at around six months of age, hearing is assessed via visually reinforced orientation audiometry (VROA). This procedure involves infants turning their head towards loudspeakers when they hear the sound. Correct responses are reinforced by the appearance of a puppet or some other visual reward. VROA allows audiologists to obtain accurate hearing thresholds across the normally audible frequency range. From around two-and-a-half years of age, infants’ hearing can be tested using play audiometry, consisting of child performing certain actions when hearing a tone. These actions include pressing a computer keyboard, putting a piece in a puzzle or putting a marble in a marble race. During this procedure, the child wears headphones, thus, information and thresholds for each ear are obtained.

The main causes of congenital HL are genetic factors, viral infections such as Zika virus, cytomegalovirus, rubella, birth complications, and substance abuse during pregnancy (Korver et al., 2018). There are four types of HL: auditory processing disorder, sensorineural, conductive, and mixed HL. Auditory processing disorder refers to issues in processing acoustic information at a neural level (Moore, 2007). Sensorineural HL refers to cases in which the acoustic signal cannot be converted into electrical signals within the inner ear or cannot be transmitted along the auditory nerve to the brain (Smith, Bale, & White, 2005). This results in permanent HL. Conductive HL occurs when the sound cannot travel freely through the outer ear and through the middle ear due to wax or fluid blockage or damage to the outer or middle ear (Dillon, 2008). This only results in the attenuation of sound and can be improved by surgical treatment. Mixed HL refers to the cases when a child experiences both sensorineural and conductive HL (Brookhouser, 1996).

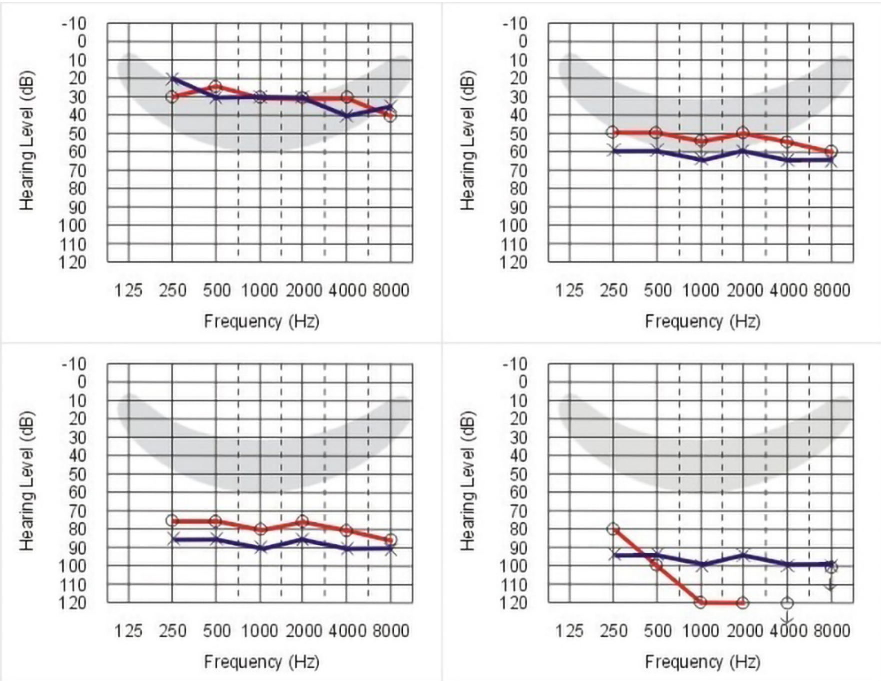

Figure 4. Hearing thresholds for mild (top left panel), moderate (top right panel), severe (bottom left panel), and profound (bottom right panel) HL. Source: https://www.aussiedeafkids.org.au/describing-the-severity-of-a-hearing-loss.html.

Regardless of the types and causes of HL, the degree of HL is defined by determining hearing thresholds (see Figure 4). As a result of threshold testing, HL can be defined as mild, moderate, severe, profound or as a combination of these. Mild HL occurs when hearing thresholds are between 21 and 40 dB (Joint Committee on Infant Hearing, 2007). As a consequence, the child may have difficulty hearing soft or distant speech as well as difficulty hearing normal conversations when there is a lot of background noise. Moderate HL refers to hearing thresholds between 41 and 70 dB and in these cases a child will need to be fitted with

Hearing Aids in order to understand normal speech (Joint Committee on Infant Hearing, 2007). A hearing threshold between 71 and 90 dB is defined as severe HL and includes difficulty in understanding normal speech even with Hearing Aids (Joint Committee on Infant Hearing, 2007). If hearing thresholds are at 91 dB or greater, this is defined as profound HL and in these cases, the child is unable to hear and understand a shouted voice even with Hearing Aids (Joint Committee on Infant Hearing, 2007). The majority of children with profound HL are implanted with Cochlear Implants. Additionally, HL can include a combination of these types such as cases when a child has, for example, a moderate HL in the low frequency plus a profound HL in the high frequency range, which would be described as moderate to profound HL.

2.2.3 Restoration of hearing.

In order to restore infants' hearing, non-implantable devices such as conventional Hearing Aids as well as implantable devices such as Cochlear Implants and Bone-anchored Hearing Aids (BAHA) are used (see Figure 5 for different types of devices). The majority of infants with mild to severe HL use conventional Hearing Aids. The main benefit of conventional Hearing Aids is that they are digital and programmable, so they can be customised to each individual's hearing ability. However, conventional Hearing Aids have some limitations including a lack of sufficient perceived benefit, complications such as tinnitus, skin irritation, itching in the ear channel, and cosmetic concerns (Moore, 1991). For infants with severe to profound HL, restoration of HL is achieved by Cochlear implantation. Due to the practice of Newborn Hearing Screening resulting in the early detection of HL, many infants undergo implantation before their first birthday (Fitzpatrick, Ham & Whittingham, 2015). In infants with conductive or mixed HL, BAHA is used. Since the implementation of BAHA requires surgery on the skull, and since these bones are very soft in infants, they may use the BAHA on a headband until they are old enough for the surgery. One of the main advantages of BAHA is improved speech understanding in noise (Myrthe, Bosman, Snik, Mylanus, & Cremers, 2005; Niparko, Cox, & Lustig, 2003).

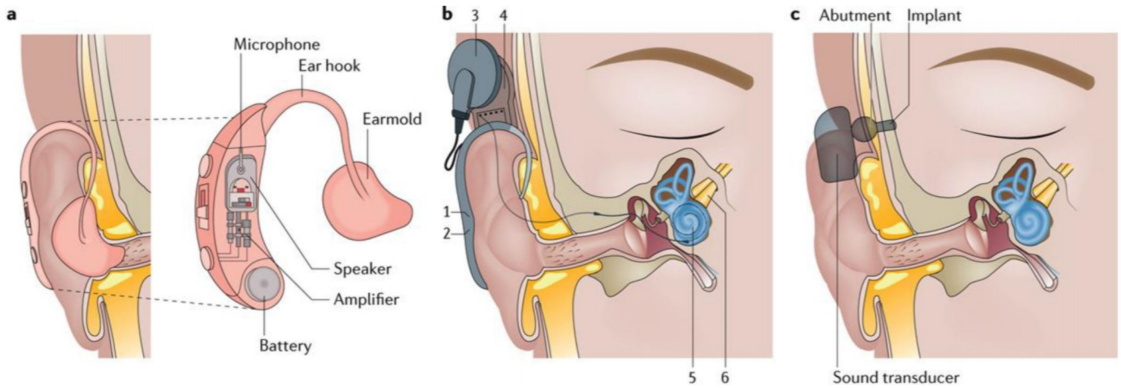

Figure 5. Restoration of HL using (a) hearing aids, (b) cochlear implants, and (c) BAHA (Figure from Korver, A. M., Smith, R. J., Van Camp, G., Schleiss, M. R., Bitner-Glindzicz, M. A., Lustig, L. R., ... & Boudewyns, A. N. (2017). Congenital hearing loss. *Nature reviews Disease primers*, *3*, 16094.).

2.2.4 Early intervention programs.

Once infants are diagnosed with HL, parents are encouraged to attend early intervention programs. In the state of New South Wales (NSW), where this project was conducted, families can attend early intervention programs free of charge provided by The Shepherd Centre, The Catherine Sullivan Centre, and The Royal Institute for Deaf and Blind Children. These three centres mainly use the auditory-verbal approach, teaching the child to develop listening skills by using residual hearing. In this approach the child is discouraged from using sign language and visual cues such as lip reading. However, services in these centres are tailored to the child's needs, and thus if sign-supported or visual-supported communication are advantageous for a child, the audiologist will use the most appropriate approach. These centres also provide other services such as counselling services for the child and family, regular speech and language assessments, and group programmes for children and parents. These centres also help children with HL in their transition to school. In Australia, around 85% of children with significant permanent HL attend regular schools (Punch, Creed, & Hyde, 2005).

However, even with restoration of hearing with implantable and non-implantable devices and early interventions, the majority of children with HL have delayed language development in comparison with their peers with NH (Moeller et al., 2007a, 2007b; Vohr, et al., 2008). In the Section 2.3 of this Chapter, various aspects of language development in infants with HL are described, followed by Section 2.6 which provides an outline of the research studies to be conducted in this thesis.

2.3 Language development in infants with hearing loss

Auditory deprivation during the first few months of life may affect neurobiological development at different levels, such as the cochlea (e.g., degeneration of spiral ganglion cells, Shepherd & Hardie, 2001), the central auditory pathway (e.g., reduction of synaptic density in the inferior colliculus, Leake & Hradek, 1988; Rebscher, Snyder, & Leake, 2001), and at higher cortical levels (e.g., organisation of the sensory cortices, Kujala, Alho, & Näätänen, 2000). This suggests that the absence of auditory input early in life may impair the development of neural pathways connecting the auditory cortex with other parts of the brain, thus, affecting the establishment of attentional and cognitive neural networks important for auditory processing. In addition, this can affect infants' speech perception, attention, and learning. Another important factor that should be considered in language development in infants with HL is auditory acuity for the signal received through Hearing Aids or Cochlear Implants. For example, it has been demonstrated that Cochlear Implant users may have limitations in extracting information from the signal about the frequency, pitch, and loudness of a sound (Macherey & Carlyon, 2014).

2.3.1 Speech perception.

Despite the limitations of the signal from Hearing Aids or Cochlear Implants, there is evidence that speech perception is evident quite early in infants with HL fitted with Hearing Aids or Cochlear Implants. First, infants with four months of device use prefer to listen to speech compared to static (white noise) and dynamic (time-reversed speech) nonspeech stimuli (Segal & Kishon-Rabin, 2011). This preference is comparable to the preference in infants with NH, and it increases with age and hearing experience (Segal & Kishon-Rabin, 2011). In addition, infants with only one to two months of experience with Cochlear Implants can discriminate basic speech pattern differences (e.g. *hop hop hop* vs. *ahhh*) and prefer their native language to a foreign language (Houston, Pisoni, Kirk, Ying, & Miyamoto, 2003; Kishon-Rabin, Harel, Hildescheimer, & Segal, 2010).

Nonetheless, Houston and colleagues (2003) tested listening preference for speech sounds versus silence in infants with Cochlear Implants before and after implantation. They found that at one to six months after Cochlear Implantation, there was no significant difference in infants' preference for speech versus silence. Although there was a large degree of variability in the data, these findings might suggest that infants with HL have reduced attention to speech, which may negatively affect language development in infants with HL.

With regards to phoneme discrimination in infants with HL findings are mixed. Some studies report that infants discriminate some vowel and consonant contrasts (e.g. /u/ - /i/, /m/ - /z/) within six months of Cochlear Implant use, and other contrasts (e.g. /i/ - /a/, /u/ - /a/, /z/ - /s/, /s/ -/j/) within 12 months of Cochlear Implant use, while experiencing difficulty with place of articulation contrasts (e.g. /z/ - /v/) even after 12 months of Cochlear Implant use (Schauwers, Gillis, Daemers, De Beukelaer, & Govaerts, 2004; Uhler, Yoshinaga-Itano, Gabbard, Rothpletz, & Jenkins, 2011). On the other hand, other studies indicate that infants with HL are able to discriminate only vowel height contrasts (e.g. ***doo*** vs. ***daa***), while struggling to discriminate vowel place contrasts (e.g. ***doo*** vs. ***dee***), and consonant contrasts (e.g. /d/-/b/;

/d/-/t/) (Eisenberg, Martinez, & Boothroyd, 2004; Martinez, Eisenberg, Bothroyd, & Visser-Dumont, 2008). The vowel place contrast (e.g. ***doo*** vs. *dee*) has been found to be discriminated by infants with mild HL (less than 40 dB), but not by infants with severe to profound HL (Martinez et al., 2008). Therefore, it could be the case that discrimination of vowel place contrasts is dependent on the severity of HL in infants.

2.3.2 Word segmentation.

One of the cues that infants with NH use to segment words from fluent speech is prosodic stress patterns. From the early days of Cochlear Implantation, stress perception has been the subject of a number of studies. These earlier studies demonstrated that after receiving Cochlear Implants or Hearing Aids, the majority of children were able to differentiate between a monosyllable and a spondee (a disyllabic word with equal stress on both syllables, and between a trochee (a disyllable with stress on the first syllable) (Osberger et al., 1991; Thielemeir, Tonokawa, Petersen, & Eisenberg, 1985). More recent studies have shown that infants and children with HL are able to detect differences in stress patterns within six months (Segal, Houston, & Kishon-Rabin, 2016) and 12 months (Core, Brown, Larsen, & Mahshie, 2014) after initiation of Cochlear Implant device use. Additionally, it has been found that within six-months of Cochlear Implant use German learning infants develop specific event-related potential (ERP) responses for iambic but not for trochaic deviants when listening to the disyllable “baba” with stress on either the first or second syllable exhibiting the same pattern in ERP responses as infants with NH (Vavatzanidis, Mürbe, Friederici, & Hahne, 2016). Given the importance of stress pattern perception for word segmentation, these findings suggest that infants with HL may have sufficient access to information to enable them to extract individual words from fluent speech. It should be noted that prosodic stress can be used as a cue for word segmentation in rhythmic languages and that there are other cues available to infants in word segmentation, such as phonotactic constraints (Mattys et al., 1999), context-sensitive allophones (Hohne & Jusczyk, 1994), and statistical regularities in the input (Saffran et al., 1996). However, to our knowledge, there are no studies that have investigated these cues in infants with HL.

2.3.3 Speech production.

A review of available evidence on speech production in infants with HL suggests that there is a delay in comparison to infants with NH. For example, the onset of canonical babble in infants with HL has been found to be approximately six-and-a-half months later than in infants with NH (Moeller et al., 2007b). Additionally, a similar delay (seven months) has been found in the acquisition of vowels, stops, nasals, glides, and liquids in infants with HL compared with infants with NH. In addition, it has been found that infants with HL produce fewer complex multisyllabic utterances and more vowel-only utterances in comparison to infants with NH (chronological age matched) (McGowan, Nittrouer, & Chenausky, 2008; Moeller et al., 2007b; von Hapsburg & Davis, 2006). In terms of receptive and expressive (productive) vocabulary development, two studies using maternal reports of vocabulary knowledge in infants with HL have been conducted (Mayne, Yoshinaga-Itano, & Sedey, 1999a; Mayne, Yoshinaga-Itano, Sedey, & Carey, 1999b). In both studies, receptive and expressive vocabularies in infants between eight and 37 months of age were assessed by administering the MacArthur-Bates Communicative Development Inventory (MCDI; Fenson et al., 1993). The results showed that infants with HL have a significant delay in receptive and expressive vocabulary development in comparison to their peers with NH. Additionally, the vocabulary spurt in these infants was observed at around 25 months of age, which is about eight months later than that observed in infants with NH. Not only do infants with HL have delayed receptive and expressive vocabulary development, but their word production at 24 months has been found to be less accurate, less intelligible, and less complex than word production of infants with NH at the same age (Moeller et al., 2007a).

The differences observed in these studies were obtained by comparing infants with HL with infants with NH who were of the same chronological age as those infants. Even though infants with HL in these studies were infants who received early intervention consisting of Hearing Aids or Cochlear Implants, age of intervention ranged from two to five months. Thus, the fact that these infants did not have access to speech sounds for approximately three months in utero and almost five months before the intervention should be taken into account. On the other hand, when infants with HL were compared to infants with NH with the same amount of hearing experience, no difference in canonical babbling was observed (Moeller et al., 2007b). This suggests that although language development in infants with HL may be delayed, it follows the same developmental stages as in infants with NH. Also, it indicates the necessity of comparing infants with HL not only with infants with NH of the same chronological age, but also with infants with NH with the same amount of hearing experience (hearing age) as well. That is why both chronological-age matched and hearing-age matched controls should be employed in studies of infants with HL. This is done in the first experiment in this thesis.

Having now discussed speech perception and production in infants with HL, given the importance of IDS in infant' language development, the following sections cover findings related to IDS to infants with HL compared to infants with NH.

2.4 Infant-directed speech to infants with hearing loss

2.4.1 Preference for IDS over ADS in infants with hearing loss.

Just a few studies have examined whether infants with HL display the listening preference for IDS over ADS typically found for infants with NH (as discussed in Section 1.4.3 in Chapter 1). Robertson, von Hapsburg, and Hay (2013) examined whether 19-month-old infants with HL who have seven months of hearing experience prefer to listen to IDS over ADS. Their preference was compared to preference in infants with NH matched by chronological age and hearing experience. They found that infants with HL prefer IDS over

ADS displaying a similar preference as infants with NH matched by hearing experience. Moreover, in another study (Wang, Bergeson, & Houston, 2018), it was found that nine-month-olds (with four months of hearing experience) display a comparable preference to IDS over ADS as do infants with NH of the same chronological age. This may suggest that infants with HL may be able to use their residual hearing before being fitted with Hearing Aids that enables them to develop age-appropriate preference for IDS. It has been found that infants with around four to eight months of hearing experience (but not those with 12 months of hearing experience) prefer to listen to IDS over ADS (Robertson et al., 2013; Wang et al., 2018). Given the findings with infants with NH that preference for specific IDS features changes with age and growing linguistic experience, it could be that the different finding for 12-month-old infants with HL was due to the use of the IDS stimuli with the same features across all age groups. As in the case in infants with NH, it could be that in infants with HL, preference for IDS is governed by different IDS features at different ages (Kitamura & Notley, 2009; McRoberts et al., 2009; Panneton et al., 2006; Segal & Newman, 2015).

Additionally, not only do infants with HL prefer to listen to IDS, they also obtain specific benefits from this preference. For example, Wang, Bergeson, and Houston (2017) found that a preference for IDS enhances attention to speech in infants with Cochlear Implants 12 months after fitting. Their findings demonstrated that IDS enhanced attention to speech in those infants. In addition, the degree of the IDS preference over ADS was related to infants' vocabulary development at 18 months after fitting. Given the findings of reduced attention to speech in infants with HL (Horn, Houston, & Miyamoto, 2007; Houston, et al., 2003), these findings suggest that IDS is nevertheless important for language acquisition in these infants.

2.4.2 Acoustic features of IDS to infants with hearing loss.

The specific focus of this thesis is on the pitch and vowel hyperarticulation in speech to infants with HL. Accordingly, the review now turns to studies that assessed these features in infants with HL. First, evidence on prosodic features of IDS to infants with HL is reviewed (Section 2.4.2.1), then, it is followed by research regarding exaggeration and variability in vowel production in IDS to infants with HL (Section 2.4.2.2).

2.4.2.1 Prosody in IDS to infants with hearing loss.

Several studies have examined prosodic features in IDS to infants with HL. The majority of these studies have compared IDS to infants with HL to IDS to two groups of infants with NH: those matched by chronological age, and those matched by the amount of hearing experience compared with infants with HL. The results of these studies indicate that mothers exaggerate pitch height (Miyamoto, Houston, & Bergeson, 2005), pitch range, pitch variability, utterance duration, and pause duration (Bergeson et al., 2006) in IDS to infants with Cochlear Implants between 10 and 37 months of age. With regards to the comparison with NH controls, it was found that mothers exaggerate pitch height (Bergeson et al., 2006; Miyamoto et al., 2005) and minimum pitch (Bergeson et al., 2006) to a similar degree to infants with NH matched by hearing experience but not with infants with NH matched by chronological age. Thus, it seems that infants' hearing experience and not chronological age influences maternal production of pitch in IDS to infants with HL.

To date, few studies have assessed the stability of features in IDS to infants with HL over the first year after device fitting. Kondaurova and Bergeson (2011) demonstrated that mothers adjust prosodic cues for clause boundaries such as pre-boundary vowel lengthening in IDS to infants with Cochlear Implants to a similar degree as do mothers in IDS to infants with NH matched by hearing experience. Further, Kondaurova, Bergeson, and Xu (2013) examined pitch height, pitch range, pitch variability, and speech rate in IDS to infants with Cochlear Implants at three, six, and 12 months post-implantation and compared them to chronologically matched and hearing-age matched NH controls. Although these features were exaggerated in speech to all three groups of infants, there was greater exaggeration for all features in IDS to infants with HL compared to controls matched by chronological age. Additionally, their findings demonstrated that pitch height, pitch range, and pitch variability were exaggerated to a similar degree in IDS to infants with HL compared to infants with NH matched by hearing age, with no change over the 12-month period. These results confirm the findings from cross-sectional studies regarding modulations in maternal IDS as an effect of the infants' hearing experience (Bergeson et al., 2006; Miyamoto et al., 2005).

Regarding infants fitted with Hearing Aids, Bergeson (2011) demonstrated different developmental trajectories for pitch height in IDS to infants with Hearing Aids compared to those with Cochlear Implants and infants with NH matched by chronological age. In this study, pitch height in maternal IDS was assessed within three, six, and 12 months of device use. The findings revealed that during the first 12 months post-implantation, mothers decrease their pitch height in speech to infants with Cochlear Implants to a similar degree as in IDS to chronological age matched NH controls. On the other hand, pitch height increased in IDS to infants with Hearing Aids at six months post-fitting compared to pitch height at three months post-fitting and then began to decrease. It could be the case that infants with Hearing Aids after six months post-fitting still benefitted from the attentional features of IDS, such that mothers produced pitch with greater degree of exaggeration at this age compared to younger ages. Since this study did not include controls with NH matched by hearing experience, it is difficult to determine whether the observed results were due to infants' chronological age or hearing experience. Results of another study (Lam & Kitamura, 2010) that investigated IDS to one infant with Hearing Aids and one infant with NH (twin siblings) showed that their mother exaggerated pitch height, pitch range, and pitch variability in IDS to the infant with HL at both 12 and 22 months of age to a similar degree as to the NH infant (Lam & Kitamura, 2010). These findings suggest similar adjustments in prosodic features of IDS to infants with HL and to infants with NH and a similar decrease in attentional features in IDS to older infants.

However, since this study consisted of IDS recordings of one mother talking to her twins, the generalisability of these findings is limited.

The evidence presented in this section suggests that the prosodic exaggeration typically found in IDS to infants with NH is also present to some degree in IDS to infants with HL suggesting that infants with HL indeed receive speech input that may benefit their language development. Additionally, these studies suggest that IDS modulations to infants with HL across development are due to infants' hearing experience rather than to maturational factors. These studies highlight the need to include NH controls matched with the same amount of hearing experience as infants with HL. Finally, the evidence presented in this section highlights the paucity of research on prosodic features in IDS to infants with Hearing Aids, which may show different patterns from those observed in IDS to both infants with Cochlear Implants and infants with NH as suggested by Bergeson (2011).

2.4.2.2 Vowel hyperarticulation in IDS to infants with hearing loss.

Regarding vowel hyperarticulation in IDS to infants with HL, data are limited. One of the first studies that examined the presence of vowel hyperarticulation in IDS to infants with HL was conducted by Lam and Kitamura (2010), who recorded IDS produced by a mother speaking to her twin sons, one with bilateral HL and the other with NH, at 12.5 months and 22 months of age. Their findings demonstrated that the mother hyperarticulated vowels in IDS to the twin with NH but not to the twin with HL despite there being no difference in vowel duration. In another study, Kondaurova, Bergeson, and Dilley (2012) investigated vowel space area and vowel duration for American English tense (/i/, /u/) and lax (/I/, / ʊ /) vowels in IDS to infants with HL prior to Cochlear Implantation and compared with chronologically age matched NH controls. They found that mothers hyperarticulate vowels to infants with HL to a similar degree as to infants with NH. The contrasting findings from these two studies may be explained by the absence of controls matched by hearing experience, variability in infants' ages, different devices used, as well as a difference in the vowels assessed.

In this regard, examination of individual first and second formant frequencies (F1 and F2) and vowel space dispersion may provide more detailed evidence on vowel production in IDS to infants with HL. Wieland and colleagues (2015) investigated vowel production in IDS to infants with Cochlear Implants and Hearing Aids between three and six months after fitting. Additionally, their study included NH controls matched by chronological and hearing age. Vowel production was examined by assessing formant frequencies, vowel space areas, and vowel space dispersion in both IDS and ADS. Their results revealed higher F1 for /i/ in IDS to infants with Hearing Aids, and higher F2 for the vowels /a/ and /i/ in IDS to infants with Cochlear Implants compared to both groups of NH controls. High F1 and F2 frequencies are important for vowel intelligibility and speech comprehension (Ferguson & Kewley-Port, 2002; 2007; Smiljanić & Bradlow, 2009), so it is possible that mothers of infants with HL compensated for their infants' HL by producing higher formant frequencies to make their vowels clearer and more intelligible.

Regarding vowel space dispersion, Wieland et al. (2015) found greater dispersion in IDS than in ADS suggesting greater vowel variability in IDS, and interestingly, this study reported greater vowel space dispersion in IDS to infants with Hearing Aids but not Cochlear Implants. However, the exact effect of HL on vowel production in IDS and an extent of the variability and exaggeration in vowel production are not clear. This thesis takes the investigation of variability in IDS further by measuring formants of individual vowels but also vowel hyperarticulation and vowel dispersion. Also, the analyses in Wieland et al. (2015) were based on a combination of speech from two recordings separated by three months. While this approach allowed the study to obtain sufficient data for analysis, using the speech to an infant at two different ages could affect the results since previous studies showed that IDS changes as a function of infant age (Kitamura et al., 2001). This possibility is investigated in Chapter 4 of this thesis.

2.5 Factors to consider in research on IDS to infants with hearing loss.

In investigating speech to infants with HL, it should be noted that there are some factors inherent to research involving these infants that can affect the results. The first factor is the variability of the auditory information perceived by infants through their device. This variability can result from the type of hearing device, the level of HL, and the configuration of the HL. For example, although Cochlear Implants successfully provide auditory access to infants with severe to profound HL, frequency discrimination with Cochlear Implants is lower (Zeng, Tang, & Lu, 2014) and the dynamic range is smaller (Zeng, 2004) compared to sound discrimination with normally functioning ears. Secondly, it is important to note that the nature of the acoustic input from Hearing Aids and from Cochlear Implants is not only significantly different from the sound coded by the hair cells in the cochlea but also significantly different from each other (Macherey & Carlyon, 2014; Zeng, 2004; Zeng et al., 2014). In Hearing Aids, the sound is amplified differently across frequencies, whereas in Cochlear Implants the sound is recorded through 23 electrodes along the length of the cochlea compared with the coding of the sound in the normally functioning ear by 10000 hair cells. In addition, the pre-requisites for fitting vary; for infants fitted with Hearing Aids the degree of HL can vary from mild to moderate, whereas for infants fitted with Cochlear Implants it can vary from severe to profound (Joint Committee on Infant Hearing, 2007).

Infants' auditory perception varies depending on whether their HL is bilateral or unilateral. For instance, infants with unilateral HL have delayed vocabulary development compared to infants with bilateral HL (Fitzpatrick et al., 2019; Välimaa et al., 2018), and infants with bilateral HL show better sound localisation acuity and speech perception in noise (Johnston, Durieux-Smith, Angus, O'Connor, & Fitzpatrick, 2009) and develop higher receptive and expressive vocabulary skills compared to infants with unilateral HL (Boons et al., 2012; Sarant, Harris, Bennet, & Bant, 2014). This may appear counterintuitive, but these results have been attributed to the possibility that unilateral amplification in infants with unilateral HL may require extra listening effort thus limiting the availability of cognitive resources for other tasks and increasing the strain on auditory working memory capacity (Jerger, 2007). While no studies to date have investigated the effects of bilateral vs. unilateral HL configuration on IDS features, differences in IDS qualities to these infants could be expected given the factors described above as well as other experiential factors such as different intervention approaches for infants with unilateral and bilateral HL, later age of fitting for infants with unilateral HL (Fitzpatrick, Whittingham, & Durieux-Smith, 2014), and greater confusion among parents of infants with unilateral HL regarding the effectiveness of intervention practices (Fitzpatrick et al., 2015).

A final important factor that must be considered in this research is the difference between chronological age and amount of post-birth hearing experience. In infants with NH, chronological age reflects language experience, and it has been shown in this literature review that pitch and affect in mothers' IDS are modified as their infants grow older and acquire more extensive language experience (Kitamura et al., 2001). In the case of infants with HL, it is unclear whether any adjustments in IDS reflect infants' chronological age or their experience with hearing and language use, i.e., their hearing age. This difference between chronological age and hearing experience in infants with HL is captured by hearing age that is calculated from the moment of hearing device activation. As discussed in earlier sections and as implemented in Chapter 3 of this thesis, one way to assess whether IDS to infants with HL is adjusted according to their chronological age or hearing age is by comparing IDS to infants with HL to two control groups of infants with NH: chronological age controls (infants with NH of the same chronological age as the infants with HL) and hearing age controls (infants with

NH with the same amount of hearing experience (post-birth) as the infants with HL (post fitting/implantation of Hearing Aids/Cochlear Implants)).

2.6. Thesis aims and research questions.

The aim of this project is to investigate the role of infant-directed speech in early language development of infants with hearing loss (HL). *The first objective* is to identify the strength and nature of particular components of IDS to infants with HL compared with those in IDS to infants with NH, and to investigate how these components might change as a function of language experience and age from nine months through to 28 months. *The second objective* is to assess how linguistic input in the first year of life impacts the development of receptive and expressive vocabulary in the second year of life in infants with HL and NH, with special emphasis on those specific components of IDS that differ in the input to infants with HL and infants with NH. *The third objective* is to evaluate the role of the specific acoustic components identified in IDS to infants with HL and in IDS to infants with NH in facilitating early lexical processing.

In order to achieve these objectives, four empirical studies were conducted, each addressing the specific research questions outlined below. The specific hypotheses for these questions are set out in the relevant experimental chapters.

1. Does hearing experience have an effect on the acoustic features of IDS, specifically hyperarticulated vowels and exaggerated prosody?

Chapter 3 presents a cross-sectional study of the acoustic features in IDS to infants with HL in comparison to IDS to infants with NH matched by chronological age and by hearing age.

2. Do the effects of hearing experience on the acoustic features of IDS, specifically hyperarticulated vowels and exaggerated prosody, vary as a function of infants' development and growing linguistic experience?

Chapter 4 involves a longitudinal investigation of the effects of infant age and changing linguistic needs on vowel and pitch production in IDS to infants with HL and infants with NH matched by hearing age.

3. Do exaggerated prosody and vowel hyperarticulation in IDS facilitate lexical processing in 18-month-old infants?

In Chapter 5, the research focus is on the effects of the vowel hyperarticulation and prosody in IDS on 18-month-old infants' lexical processing.

4. Do exaggerated prosody and vowel hyperarticulation in IDS affect lexical processing in six- and 10-month-old infants at the neural level?

Chapter 6 will assess the effects of the vowel hyperarticulation on lexical processing at the neural level in six- and 10-months old infants.

The results of these experiments will add to our understanding of the potential effect of HL on maternal IDS as well as whether observed adjustments in IDS to infants with HL are the result of infants' chronological age or their amount of hearing experience. Additionally, these experiments will help us to understand the particular roles of exaggerated pitch and vowel hyperarticulation in IDS in lexical processing in infants at different stages of lexical development.

CHAPTER 3

Acoustic Features of IDS to Infants with Hearing Loss

3.1 Introduction

This chapter investigates the qualities of IDS to infants with HL. As discussed in Chapter 2, congenital HL has significant negative effects on children's early development and later quality of life including speech and language acquisition, literacy, mental health, social and cognitive functioning, and academic achievement (Moeller et al., 2007; Qi & Mitchell, 2011; Wake et al., 2004). Infants born with congenital HL have more limited access to auditory input both before and after birth (Moeller & Tomblin, 2015), and the auditory input that they receive is degraded since the nature of the acoustic input is significantly different from the sound conducted through a normally functioning ear (Macherey & Carlyon, 2014; Zeng, 2004; Zeng et al., 2014). However, after birth, this early deprivation can be mediated by Hearing Aids or Cochlear Implants, which may facilitate infants' early access to linguistic input. The linguistic input that these infants receive during their first years after intervention plays a fundamental role in their early language development, but there is no clear indication whether the quality (Lam & Kitamura, 2010; Wieland et al., 2015) and quantity (Vanormelingen, De Maeyer, & Gillis, 2016) of the early linguistic input to infants with HL differs from their peers with NH. This Chapter investigated this issue by focusing on the acoustic features of speech directed to infants with HL as a function of their age and hearing experience, compared with chronological- and hearing age-matched controls with NH.

As reviewed in Chapter 2, Section 2.4.2, research on IDS to infants with HL has focused primarily on heightened pitch and vowel hyperarticulation due to their proposed attention-getting and language development functions respectively. With regard to pitch, the degree to which mothers exaggerate pitch in their IDS appears to be modulated by their infants' hearing experience and not maturational factors. Mothers have been found to exaggerate pitch height (Bergeson et al., 2006) and pitch range (Miyamoto et al., 2005) in speech to infants with HL between 10 and 37 months to a similar degree to controls with NH matched by hearing age and not by chronological age (infants' chronological age ranged from three to 18 months in this study). With regard to vowel hyperarticulation, the evidence is more mixed. While some previous studies have argued that vowel hyperarticulation is not present in IDS to infants whose ability to hear speech is impaired (Lam & Kitamura, 2010; 2012), recent research suggests that mothers do hyperarticulate vowels to infants with Cochlear Implants between 11 and 27 months to a similar degree as to chronological- and hearing-age-matched controls with NH (Wieland et al., 2015) and to 11-month-old profoundly deaf infants prior to Cochlear Implantation compared to infants with NH (Kondaurova et al., 2012).

Therefore, it is not clear whether vowel hyperarticulation is consistently present in IDS to all infants with HL. More detailed evidence on mothers' vowel production in IDS to infants with HL comes from direct measures of individual formant frequencies (F1 and F2) and vowel space dispersion. Regarding formant frequencies, Wieland et al. (2015) found higher F1 for /i/ in IDS to infants with Hearing Aids, and higher F2 for the vowels /a/ and /i/ in IDS to infants with Cochlear Implants compared to infants with NH both chronologically and hearing-age matched. High F1 and F2 frequencies are important for vowel intelligibility and speech comprehension (Ferguson & Kewley-Port, 2002; 2007; Smiljanić & Bradlow, 2009), so it could be that mothers of infants with HL compensate for their infants' HL by producing higher formant frequencies to make their vowels clearer and more intelligible. With regard to vowel space dispersion, Wieland et al. (2015) found greater dispersion in IDS than in ADS suggesting greater vowel variability in IDS, and interestingly, this study reported greater vowel space dispersion in IDS to infants with Hearing Aids but not Cochlear Implants.

Wieland et al. (2015) study is directly related to the aims of this thesis. However, the specific effect of HL on vowel production in IDS and the specific locus of the variability and exaggeration in vowel production are not clear from Wieland et al. (2015) study. In this thesis variability in IDS is further investigated by measuring not only vowel hyperarticulation and vowel dispersion, but more specifically the formants of the individual vowels. In addition, the analyses in Wieland et al. (2015) were based on a combination of speech from two recordings separated by three months. While this approach made sufficient data available for analysis, using the speech to infants at two different ages could affect the results since previous studies have shown that IDS changes as a function of infant age (Kitamura et al., 2001). This aspect, maternal changes in IDS over infant age, is also investigated in this thesis (see Chapter 4).

As already discussed in Chapter 1 Section 1.4, it has been proposed that IDS serves three roles in infants' early development: to communicate affect to infants (Papoušek et al., 1990; Trainor et al., 2000), to attract and maintain infants' attention (Cooper & Aslin, 1990; Fernald & Simon, 1984), and to aid language acquisition (Fernald & Mazzie, 1991; Kuhl, 2000). Two acoustic components of IDS, exaggerated pitch and vowel hyperarticulation, have been proposed to serve a language acquisition role, and they will be the focus of this experiment.

The linguistic function of IDS has been supported by evidence that suggest that infants are more successful in a number of language processing tasks when stimuli are presented in IDS compared to ADS. Specifically, it has been found that the distinctive prosody of IDS facilitates infants' speech discrimination (Trainor et al., 2000), word segmentation (Thiessen et al., 2005), and novel word-referent mapping (Graf Estes & Hurley, 2013; Ma et al., 2011). Additionally, slow speaking rate and vowel hyperarticulation in IDS have been shown to promote infants' efficiency in spoken language processing (Song et al., 2010) and vowel discrimination (Peter et al., 2016; Zhang et al., 2011). At the individual level, mothers' vowel hyperarticulation also has been linked to the development of their infants' speech perception and lexical skills (Liu et al., 2003; Hartman et al., 2017; Kalashnikova & Burnham, 2018). Thus, IDS not only attracts infants' attention to speech and facilitates their language processing, but it also appears to facilitate the development of their speech perception and vocabulary growth.

The assumption that vowel hyperarticulation in IDS serves a linguistic function contrasts with recent evidence suggesting a lack of vowel hyperarticulation in IDS in some languages such as Dutch, Norwegian, Japanese, and Cantonese (Benders, 2013; Dodane & Al-Tamimi, 2007; Englund, 2018; Englund & Behne, 2005; Martin et al., 2015; Wong & Ng, 2018). Importantly, even in cases where vowel hyperarticulation is present in IDS, it has been noted that vowel production in IDS is more variable than in ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). Such variability leads to overlap in vowel categories, which could impede discrimination and acquisition of these categories. Furthermore, this evidence casts doubt over the claim that vowel hyperarticulation in IDS stems from parents' implicit intention to facilitate their infants' language acquisition and thus that it plays a dedicated role in early language development (Cristia, 2013).

Although the evidence suggests a presence of high vowel variability in IDS, the effects of this variability on infants' language acquisition are not clear. One of the main reasons for this is that different studies use different definitions and measures of vowel variability (see Chapter 1, Section 1.4.2.6 for a detailed description of these measures). Three measures used in previous studies that are used in this experiment are *vowel space dispersion* as a measure of within-category variability (Bradlow et al., 1996; Wieland et al., 2015), *formant dispersion* (Englund, 2018; McMurray et al., 2013), and *distances between first and second formant frequencies* for corner vowels /a, i, u/ (Bradlow et al., 1996).

The combination of vowel space dispersion and variability measures allows the construction of specific predictions regarding the linguistic role of IDS. If there is greater *vowel space dispersion* in IDS compared to ADS, it would suggest that caregivers implicitly enhance vowel categories in their IDS, thus facilitating infants' vowel acquisition. This would support a linguistic role of vowel hyperarticulation. On the other hand, the presence of greater *variability* in IDS vowels compared to ADS would support the view that vowel hyperarticulation is a by-product of other IDS features such as smiling (Fagel, 2010). However, it should be noted that even if IDS showed greater variability in vowel production, this could be an effect of producing more exaggerated vowels, and it could improve vowel robustness (Kuhl et al., 1997). On the other hand, the presence of greater variability in the absence of expanded vowels could indicate variability in fundamental frequency as the source of formant variability (Cristia & Seidl, 2014); variability which has been shown to improve infants' vowel discrimination (Trainor & Desjardins, 2002) and non-linguistic processing (Kaplan, Goldstein, Huckeby, & Cooper, 1995; Kaplan & Owren, 1994).

1.1.1 Chapter aims and research questions.

The main goal of this Chapter is to investigate the acoustic features in IDS to infants with HL specifically focusing on the effects of infants' chronological age and hearing age on the acoustic components of their mothers' IDS. For this purpose, IDS to infants with HL was compared to IDS to both chronological- and hearing-age controls with NH. Previous research has indicated that infants with HL may receive exposure to IDS that is qualitatively different from the input of chronological- or hearing-age matched infants with NH (Bergeson et al., 2006; Kondaurova et al., 2012; Lam & Kitamura, 2010; Miyamoto et al., 2005). However, the exact nature and implications of these differences remain unclear. It is possible that mothers unconsciously produce clearer IDS that has speech categories that are easier to perceive and discriminate. On the other hand, it is possible that the speech sound exaggeration component is absent in IDS to infants with HL as mothers may abandon this adjustment to compensate for the need to produce more acoustically variable IDS to capture and maintain their infants' attention to speech. To test these possibilities, a combination of exaggeration and variability measures of vowels and pitch in IDS was incorporated in this study: vowel hyperarticulation, pitch height, vowel space dispersion, formant dispersion, F2-F1 distances, and variability in pitch production.

Below we outline the specific research questions and predictions for this study:

1. *Does IDS contain more acoustic exaggeration (hyperarticulated vowels and exaggerated prosody) compared to ADS?* According to previous studies (Wieland et al., 2015), we expect to find more acoustic exaggeration (hyperarticulated vowels as well as exaggerated prosody evident in greater pitch height, and greater pitch variation) in IDS compared to ADS for all three groups of infants.
2. *Is IDS characterised by more variability in vowel production compared to ADS?* In order to assess variability in vowel production, three different measures were adopted: vowel space dispersion, formant dispersion, and F2-F1 distances for corner vowels (/a, i, u/). Vowel space dispersion was operationalised as the Euclidean distance of each vowel token from a central point in the speaker's vowel space (Bradlow et al., 1996). Greater vowel space dispersion in IDS compared to ADS would provide evidence of vowel enhancement in IDS (Bradlow et al., 1996; Wieland et al., 2015). The formant dispersion measure assesses differences in the limits of the distributions associated with vowel categories across registers. This measure was calculated in order to compare our results with previous findings that IDS has greater variability compared to ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). The observation of greater variability in IDS relative to ADS would provide evidence for vowel clarity deterioration rather than enhancement in this register. Since both /i/ and

/a/ are characterised by extreme separation of F1 and F2 formant frequencies, the observation of greater F2-F1 distance for vowel /i/ and shorter F2-F1 distance for vowel /a/ in IDS compared to ADS would provide evidence of vowel enhancement (Bradlow et al., 1996).

3. *Does hearing experience have an effect on acoustic features of IDS?* If mothers adjust their speech due to their infants' HL, then different features in IDS to infants with HL compared to IDS to both chronological- and hearing-age matched controls are expected. If this is the case, we expect to find differences in IDS to infants with HL compared to both groups of infants with NH (Kondaurova et al., 2012; Lam & Kitamura, 2010). However, if mothers adjust their speech due to infants' hearing experience, then we except to find that IDS to chronological age-matched controls with NH will differ from IDS to infants with HL and hearing age-matched controls.

3.2 Method

3.2.1 Participants.

Three groups of mother-infant dyads participated. In the HL group, there were 20 dyads in which the infant had congenital HL (HL group; *Mean Age* = 15.09 months, *SD* = 9.06, *Age range* = 7.17 – 35.86, 10 female). This group comprised 11 infants with mild to moderate HL, 9 with severe to profound HL, 14 infants with bilateral HL and 6 with unilateral HL (see Table 1 for further details). Twenty infants with NH were matched by chronological age to the infants with HL (NH-CA group, *Mean Age* = 15.37 months, *SD* = 8.87, *Age range* = 6.90 – 35.86, 7 female) and 20 were matched by hearing age (NH-HA group, *Mean Age* = 11.68 months, *SD* = 8.43, *Age range* = 5.23 – 32.48, 6 female).

Table 1. *Chronological (CA) and Hearing age (HA) at testing (months), HL degree and configuration, HL device and aetiology of HL for infants with HL*

ID	CA (HA)	HL degree	Configuration	Device	Aetiology
1	9.2 (7.70)	mild/moderate	bilateral	Hearing Aids	connexion 26
4	10.59 (9.09)	mild/moderate	bilateral	Hearing Aids	genetic
5	9.4 (6.60)	severe/profound	bilateral	Cochlear Implants	congenital
6	14.6 (6.60)	R: mild	unilateral	BCHA*	microtia
7	29.29 (8.29)	/	bilateral	Hearing Aids	sensory neural
8	23.83 (21.83)	mild	bilateral	Hearing Aids	unknown
9	12.06 (7.06)	moderate/severe	bilateral	Hearing Aids	birth
10	8.28 (5.78)	moderate	bilateral	Hearing Aids	sensorineural
11	7.17 (5.17)	moderate	bilateral	Hearing Aids	unknown
12	24.82 (32.32)	severe	bilateral	Cochlear Implants	Enlarged vestibular aqueducts
13	8.25 (5.75)	mild/moderate	bilateral	Hearing Aids	unknown
14	21.99 (16.59)	profound	bilateral	Cochlear Implants	unknown (genetic history)
15	35.96 (32.86)	R: moderate/severe	unilateral	BCHA	microtia and atretia
16	8.02 (6.02)	R: moderate	unilateral	BAHA** 5 softband	microtia and atretia
18	17.06 (7.56)	moderate	bilateral	Phonak Sky V50 P	unknown
23	15.45 (15.45)		unilateral	Hearing Aid	unknown
24	24.13 (24.13)	L: mild/moderate	unilateral	Unaided	unknown
25	17.98 (7.53)	L: severe; R: profound	bilateral	Cochlear Nucleus 7 processor	connexion 26
26	10.52 (10.52)	R: unknown	unilateral	N/A	sensorineural
29	8.09 (6.59)	L: moderate/severe R: severe	bilateral	Hearing Aids	unknown

* BCHA – Bone Conduction Hearing Aid ** BAHA – Bone-Anchored Hearing Aid

All mothers were native speakers of Australian English and had normal hearing (*Mean age* = 33.66, *SD* = 4.74), and all infants were monolingual, born full-term, and were not at-risk for any additional developmental disorders. Mothers' median education level was a University (bachelor) degree, and a Kruskal Wallis H test showed that education level did not differ across the three groups ($\chi^2(2) = 2.06$, $p = .36$). Five mother-infant dyads (2 HL, 2 NH-CA, and 1 NH-HA) were detected as outliers (hyper-scores for vowel hyperarticulation were higher than three standard deviations from the mean). These five dyads and dyads from their corresponding matched groups were excluded from analyses (15 dyads excluded in total). Thus, the final sample comprised 45 dyads, 15 with HL, 15 NH-CA, and 15 NH-HA.

3.2.2 Procedure.

Mothers' speech was recorded in two types of situations: a play session with their infant (IDS) and a semi-structured interview with an adult experimenter (ADS). The IDS play sessions were recorded in a quiet room inside an infant laboratory or a clinic. Mothers were provided with three toys, a sheep, a shoe, and a shark, and were instructed to play with their infants naturally as they would do at home. These toys were chosen in order to elicit the target words *sheep*, *shoe*, and *shark* (note that 'r' is non-rhotic in Australian English) and mothers were not aware that the specific vowels /a, i, u/ were the focus of this study. Mothers wore a head-mounted microphone (AudioTechnica A892) feeding into Adobe Audition CS6 software via an audio input/output device (MOTU Ultralite MK3). The ADS sessions were conducted in the same way in the absence of the infant. During this session, a female experimenter, a native speaker of Australian English, interviewed each mother about the IDS session, eliciting the same three target words. IDS and ADS sessions lasted between 5 and 7 minutes each.

3.2.3 Analyses.

3.2.3.1 Pitch.

In order to analyse pitch, IDS and ADS recordings were separated into audio segments using Praat software (Boersma & Weenink, 1996). The segments were defined as a period of mother's speech not interrupted by the infant's vocalisations or noises from the environment.

From these audio segments, mean fundamental frequency (F0) was extracted. Since pitch perception is logarithmic by nature, all F0 values were converted from Hz into perceptual units (Mels) using the following formula for pitch height:

$$Semitone = 12LOG_2(F0)$$

As a measure of pitch variation, standard deviations (SD) for F0 were calculated in both registers.

3.2.3.2 Vowel hyperarticulation.

For analyses, the target words *sheep*, *shoe,* and *shark* were identified in each IDS and ADS recording, their onset and offset were manually determined, and then each word was extracted. Next, the target corner vowels /a, i, u/ were extracted from each word (see Table 2 for mean number of extracted vowels). Praat scripts were then used to obtain the values for vowel duration, F0, F1, and F2 for each vowel. The formant values used were mean value in Hz from the 40% and 80% points of each vowel's duration (Munhall, MacDonald, Byrne, & Johnsrude, 2009). Mean F1 and F2 values in Hz were used to calculate vowel space area separately for IDS and ADS as a measure of vowel hyperarticulation. For vowel space area calculations, the following formula was used:

$$\textit{Vowel area} = \text{ABS } \tfrac{1}{2} \times [(\text{F1/a/} \times (\text{F2/i/ - F2/u/}) + \text{F1/i/} \times (\text{F2/u/ - F2/a/}) + \text{F1/u/} \times (\text{F2/a/ - F2/i/})]$$

3.2.3.3 Variability in vowel production.

Vowel space dispersion was calculated by identifying the centroid of each speaker's vowel space triangle and then computing the distances of individual vowel tokens from the centroid (Bradlow et al., 1996; Wieland et al., 2015). Vowel space dispersion was calculated for both IDS and ADS. Formant dispersion was calculated using standard deviations for F1 and F2 (Cristia & Seidl, 2014; Englund, 2018) for each corner vowel separately for IDS and ADS. The measure of F2-F1 distances was calculated by subtracting F1 values from F2 values separately for /a/, /i/ and /u/ in both IDS and ADS.

Table 2. *Mean number (SD) of vowels used for calculating formant frequencies in IDS and ADS for infants with HL, NH-CA, and NH-HA infants*

	IDS HI	IDS CA	IDS HA	ADS HI	ADS CA	ADS HA
N/a/	9.67 (3.77)	10.87 (5.28)	10.87 (5.51)	5.6 (1.45)	5.6 (1.55)	5.8 (2.01)
N/i/	9.47 (4.85)	10.67 (6.13)	11.6 (5.85)	4.13 (1.06)	4.93 (1.71)	5.4 (1.24)
N/u/	10.47 (5.72)	11.21 (5.26)	8.93 (6.85)	4.8 (2.57)	5 (1.81)	4.2 (1.82)

3.3 Results

The results are presented in four parts relating to vowel production in IDS to infants with HL and two groups of infants with NH, as well as pitch production to infants with HL and two groups of infants with NH. These analyses were conducted to test the hypotheses for this experiment. Two additional sets of exploratory analyses were included to assess the acoustic features of IDS to infants with Cochlear Implants and Hearing Aids, as well as the acoustic features to infants with bilateral and unilateral HL. First, hyper-scores for vowel articulation (vowel triangle area), vowel space dispersion, and pitch were calculated by dividing each mother' IDS scores by her own corresponding ADS scores. This controls for individual differences by using each speaker's ADS productions as their own baseline (Kalashnikova & Burnham, 2018), and importantly, it captures *the degree to which each feature is exaggerated* in IDS compared to each mother's ADS. In these, scores above 1 signify *hyper*articulation: expanded vowel triangle, more dispersed vowels, heightened pitch in IDS compared to ADS. Scores below 1 signify *hypo*articulation: reduced vowel triangle, less dispersed vowels, reduced pitch compared to ADS. Finally, scores of 1 signify that IDS productions were not different from ADS. One-sample *t*-tests were used to compare each hyper-score to the value of 1 and univariate ANOVAs with hyper-scores as the dependent variables and Group as the independent variable were conducted to compare hyper-scores for vowel articulation, vowel space dispersion, and mean pitch across the three groups of infants (see Figure 6 for hyper-scores and Table 3 for the summary of *t*-test results).

3.3.1 Vowel production in IDS.

Vowel hyperarticulation. The one-sample *t*-tests showed that in IDS to all three groups of infants, mothers did not expand or reduce their vowel space compared to their ADS. The univariate ANOVA demonstrated no significant group effect ($F(2, 42) = 0.61$, $p = .55$, $\eta_p^2 = .03$)[1] (see Figure 7 for vowel triangles).

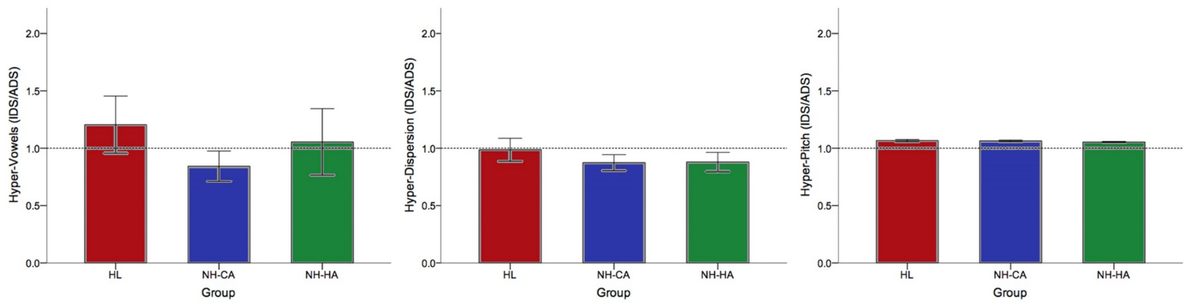

Figure 6. Hyper-scores for vowel articulation, vowel space dispersion, and mean pitch for infants with HL, NH-CA and NH-HA infants (error bars represent SEM).

[1] Given the wide age range included in this study, additional Analyses of Covariance were conducted with hyper-scores for vowel area, dispersion, and pitch as dependent variables, group as the independent variable and age in months as the covariate. Results yielded identical patterns to the analyses reported above. That is, after controlling for the effect of the age on hyper-scores, there was no significant difference across the three groups in vowel space areas ($F(2, 41) = .59$, $p = .56$, $\eta_p^2 = .03$), vowel space dispersion ($F(2, 41) = .51$, $p = .61$, $\eta_p^2 = .02$), and in pitch ($F(2, 42) = 1.79$, $p = .18$, $\eta_p^2 = .08$). Importantly, there were no significant effects of age on vowel area ($F(2, 41) = .62$, $p = .43$, $\eta_p^2 = .02$), vowel space dispersion ($F(2, 41) = .15$, $p = .70$, $\eta_p^2 = .01$) and, but there was a significant effect of age on pitch ($F(2, 41) = 8.64$, $p = .01$, $\eta_p^2 = .17$).

Table 3. *Results of one-sample t-test analyses (Cohen's d) comparing hyper-vowel, hyper-dispersion, and hyper-pitch scores to 1 (df=14) in IDS to infants with HL, NH-CA, and NH-HA infants*

Group	Hyper-vowels	Hyper-dispersion	Hyper-pitch
HL	.82 (.22)	-.13 (.03)	6.88** (1.75)
NH-CA	-1.19 (.31)	-1.81 (.48)	8.82** (2)
NH-HA	.19 (.05)	-1.44 (.38)	11.37** (2.5)

**$p < .001$

Vowel space dispersion. As can be seen in Table 3, the one-sample *t*-tests indicated that mothers produced vowels with a similar amount of dispersion in IDS to all three groups of infants as compared to ADS. The univariate ANOVA showed no significant difference across the three groups ($F(2, 42) = .55$, $p = .58$, $\eta_p^2 = .03$).

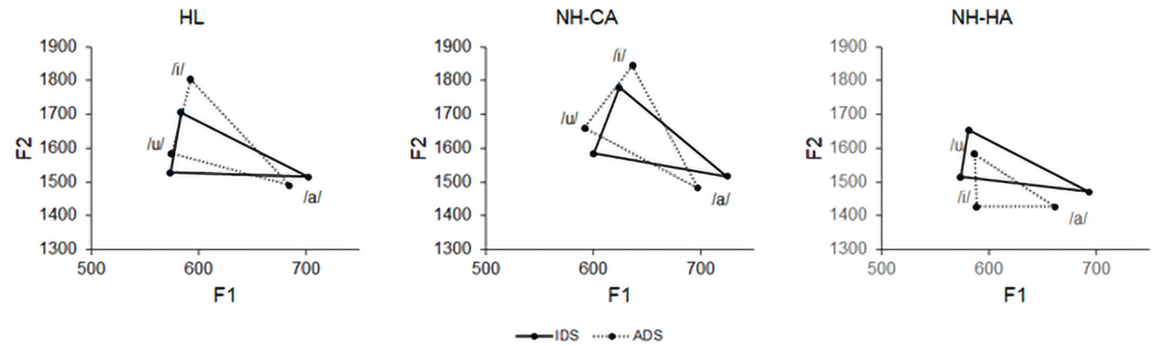

Figure 7. Vowel triangle areas for IDS and ADS for infants with HL, NH-CA, and NH-HA

Formant dispersion. Formant dispersion in IDS to infants with HL, NH-CA, and NH-HA is depicted in Figure 8. To assess the variability across the tokens for each corner vowel, measures of F1 and F2 standard deviations in IDS and ADS were used. Two 2 (Speech Register: IDS, ADS) × 3 (Group: HL, NH-CA, and NH-HA) mixed-measures ANOVAs, one for F1 and one for F2, were conducted separately for each vowel /a/, /i/, and /u/. The results of the ANOVAs are presented in Table 4 and the findings are summarised below.

Vowel /a/. Formant dispersion for F1 was significantly greater in IDS (*M* = 89.90, *SE* = 4.04) compared to ADS (*M* = 77.05, *SE* = 4.04), *p* = .03. It was above the alpha level of 0.05 for F2 (IDS: *M* = 122.34, *SE* = 6.60; ADS: *M* = 104.03, *SE* = 6.72), *p* = .08, with no significant differences across groups, and no significant interaction.

Vowel /i/. Formant dispersion for F1 did not differ across the speech registers, groups, and there was no significant interaction. Formant dispersion for F2 was significantly greater in IDS (*M* = 299.19, *SE* = 12.64) compared to ADS (*M* = 243.86, *SE* = 14.87), *p* = .01, with no significant differences across groups, and no significant interaction.

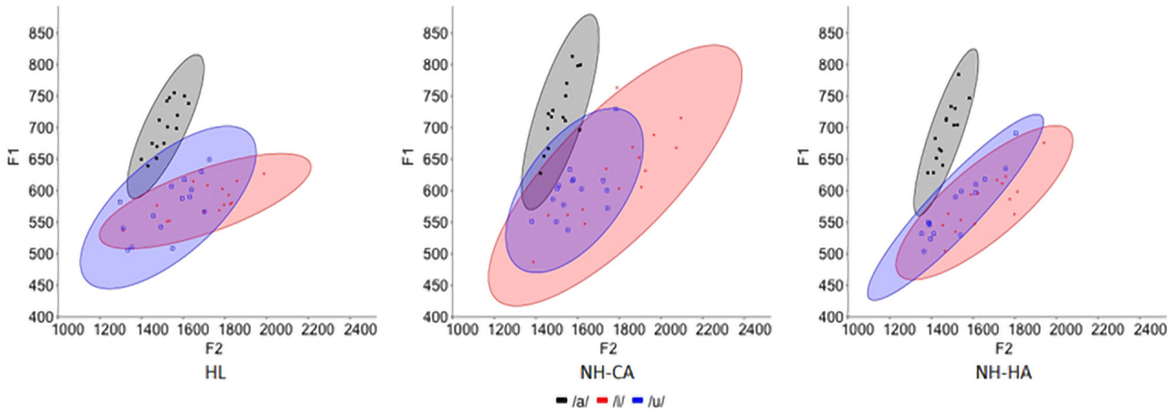

Figure 8. Distributions of vowels /a, i, u/ in IDS to HL, NH-CA and NH-HA infants (ellipses represent 95 % CI).

Vowel /u/. Formant dispersion for F1 and F2 did not differ across the speech registers, groups, and there was no significant interaction.

Summary. These results indicate that formant dispersion for /a/ and /i/ but not for /u/ was greater in IDS compared to ADS, suggesting more variability in IDS but with no difference across the three groups of infants.

Table 4. *Analyses of formant dispersion in IDS and ADS using 2 (Speech Register: IDS, ADS) x 3 (Group: HL, NH-CA and NH-HA) mixed-measures ANOVAs for vowels /a, i, u/ (N = 45)*

	Register (IDS vs. ADS) (df = 1, 42)	Group (HL vs. NH-CA vs. NH-HA) (df = 2, 42)	Register x Group (df = 2, 42)
/a / F1	$F = 4.85, p = .03, \eta_p^2 = .104$	$F = .58, p = .56, \eta_p^2 = .03$	$F = .06, p = .94, \eta_p^2 = .01$
F2	$F = 3.32, p = .08, \eta_p^2 = .07$	$F = .15, p = .86, \eta_p^2 = .01$	$F = 1.21, p = .31, \eta_p^2 = .05$
/i/ F1	$F = 1.16, p = .29, \eta_p^2 = .03$	$F = 2.02, p = .15, \eta_p^2 = .09$	$F = .21, p = .81, \eta_p^2 = .01$
F2	$F = 8.12, p = .01, \eta_p^2 = .16$	$F = 2.84, p = .07, \eta_p^2 = .03$	$F = .06, p = .94, \eta_p^2 = .01$
/u/ F1	$F = 3.57, p = .07, \eta_p^2 = .08$	$F = .63, p = .54, \eta_p^2 = .03$	$F = .98, p = .38, \eta_p^2 = .04$
F2	$F = .03, p = .86, \eta_p^2 = .01$	$F = .21, p = .81, \eta_p^2 = .01$	$F = .58, p = .57, \eta_p^2 = .03$

F2 - F1 distances. To compare the F2-F1 distances, a repeated-measures ANOVAs were conducted with Speech Register (IDS, ADS) as a repeated factor and Group as a between-subject factor separately for each vowel. For the vowel /a/, the ANOVA showed a main effect of Group ($F(2, 42) = 6.09$, $p = .01$, $\eta_p^2 = .22$). A follow up univariate ANOVA with F2-F1 distance for /a/ as the dependent variable and Group as the independent variable demonstrated that the separation between F1 and F2 was wider in IDS to infants with HL ($M = 813.27$, $SD = 39.73$) compared to NH-HA ($M = 778.08$, $SD = 28.82$), $p = .04$, but not compared to the NH-CA group ($M = 791.92$, $SD = 42.44$), $p = .38$. There was no significant difference in F2-F1 distances for vowel /a/ between NH-CA and NH-HA groups, $p = .95$. There was no significant difference between speech registers ($F(1, 42) = 1.41$, $p = .24$, $\eta_p^2 = .03$), and no significant interaction of Speech Register and Group ($F(2, 42) = .05$, $p = .95$, $\eta_p^2 = .01$). For the vowel /i/, the ANOVA demonstrated a main effect of Speech Register ($F(1, 42) = 7.17$, $p = .01$, $\eta_p^2 = .15$). The separation between F1 and F2 was wider in ADS ($M = 1185.69$, $SD = 176.13$) compared to IDS ($M = 1117.03$, $SD = 148.42$), $p = .01$. There was no significant difference between groups ($F(2, 42) = 1.29$, $p = .29$, $\eta_p^2 = .06$), and no significant interaction of Speech Register and Group ($F(2, 42) = .18$, $p = .83$, $\eta_p^2 = .01$). For the vowel /u/, the ANOVA demonstrated a main effect of Speech Register ($F(1, 42) = 11.01$, $p = .01$, $\eta_p^2 = .21$). The separation between F1 and F2 was wider in ADS (*M* = 1024.88, *SD* = 148.32) compared to IDS (*M* = 960.21, *SD* = 106.77), $p = .01$. There was no main effect of Group ($F(2, 42) = 1.11$, $p = .34$, $\eta_p^2 = .05$), and no significant interaction of Speech Register and Group ($F(2, 42) = .25$, $p = .78$, $\eta_p^2 = .01$).

3.3.2 Pitch production in IDS.

Exaggeration. Mothers significantly exaggerated pitch in IDS compared to ADS to all three groups of infants (see Table 3). The univariate ANOVA demonstrated no significant group effect ($F(2, 42) = .78$, $p = .46$, $\eta_p^2 = .04$).

Variability. In order to compare pitch variability, a repeated-measures ANOVA was conducted with Speech Register (IDS, ADS) as a repeated factor and Group as a between-subjects factor. The results demonstrated a main effect of Speech Register ($F(1, 54) = 52.10$, $p < .001$, $\eta_p^2 = .491$); pitch variation was greater in IDS (*M* = 35.49, *SD* = 15.52) compared to ADS (*M* = 17.98, *SD* = 8.95), $p < .001$. There was no significant difference between groups ($F(2, 54) = 1.24$, $p = .30$, $\eta_p^2 = .04$), and no significant interaction of Speech Register and Group ($F(2, 54) = .16$, $p = .85$, $\eta_p^2 = .01$).

3.3.3 Acoustic features in IDS to infants with Cochlear Implants and Hearing Aids.

Given that the type of intervention is one of the factors that can impact infants' language development (Bergeson, 2011; Wieland et al., 2015), additional exploratory analyses were conducted to compare the acoustic components of IDS to infants with Cochlear Implants (n = 4) and Hearing Aids (n = 9) in this sample. One-sample *t*-tests were used to compare vowel articulation and pitch hyper-scores to 1, and two separate univariate ANOVAs with hyper-scores as dependent variables and Group as the independent variable were conducted to assess the effects of intervention type on the hyper-scores (see Figure 9 for hyper-scores and Table 5 for the summary of *t*-test results).

Table 5. *Results of one-sample t-test analyses (Cohen's d) comparing hyper-vowel and hyper-pitch scores to 1 (df = 3 for group with Cochlear Implants, df = 8 for group with Hearing Aids) in IDS to infants with Cochlear Implants and Hearing Aids*

Type of Intervention	Hyper-vowels	Hyper-pitch
Cochlear Implants	-.65 (.33)	2.16 (1.08)
Hearing Aids	1.86 (.62)	5.70** (1.50)

**p<.001

Vowel hyperarticulation. As can be seen in Table 5, mothers did not expand or reduce their vowel space when addressing infants with Cochlear Implants and Hearing Aids, and there was no significant difference between the two groups ($F(1, 11) = 2.46$, $p = .14$, $\eta_p^2 = .18$) (see Figure 10 for vowel triangles).

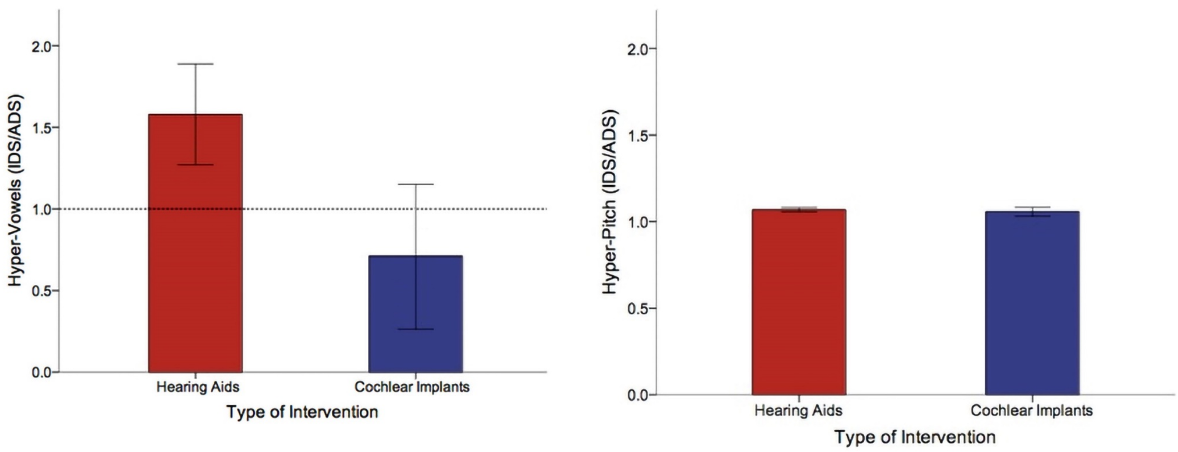

Figure 9. Hyper-scores for vowel articulation and mean pitch for infants with Cochlear Implants and Hearing Aids (error bars represent SEM).

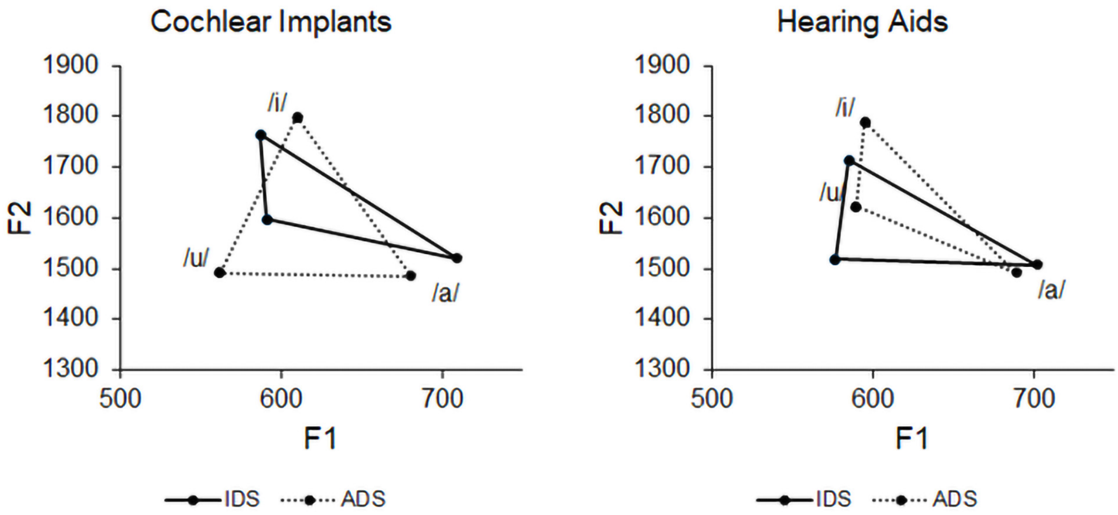

Figure 10. Vowel triangle areas for IDS and ADS for infants with Cochlear Implants and Hearing Aids.

Pitch. The *t*-tests indicated that mothers produced hyper-articulated pitch in IDS to infants with Hearing Aids, but not in IDS to infants with Cochlear Implants (see Table 5). However, the group effect was not statistically significant ($F(1, 11) = .22, p = .65, \eta_p^2 = .02$).

3.3.4 Acoustic features in IDS to infants with unilateral and bilateral hearing loss.

As described in the Chapter 2, Section 2.5, hearing configuration is a factor that can impact language development in infants with HL, but it has never been investigated in relation to IDS. Our sample included 5 infants with unilateral HL and 10 infants with bilateral HL. Thus, we conducted additional exploratory analyses comparing the acoustic components of IDS directed to these infants. One-sample *t*-tests were used to compare vowel articulation and pitch hyper-scores to 1, and two separate univariate ANOVAs with hyper-scores as dependent variables and Group as a factor were conducted to assess the effects of hearing configuration on the hyper-scores (see Figure 11 for hyper-scores and Table 6 for the summary of *t*-tests results).

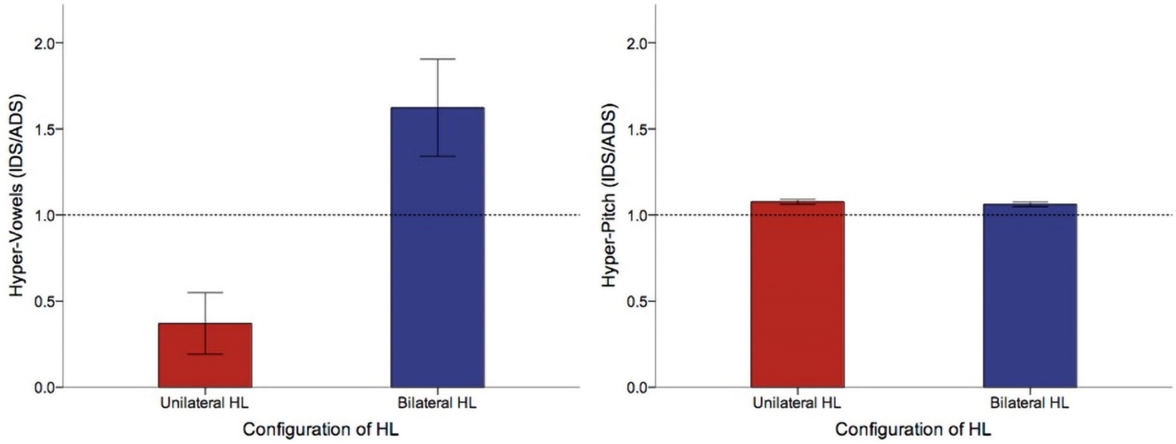

Figure 11. Hyper-scores for vowel articulation and mean pitch for infants with unilateral and bilateral HL (error bars represent SEM).

Vowel hyperarticulation. As can be seen in Table 6, mothers *hyper*-articulated vowels when addressing infants with bilateral HL, but *hypo*-articulated vowels in IDS to infants with unilateral HL. The univariate ANOVA yielded a significant effect of HL configuration, $F(1, 13) = 8.71$, $p = .01$, $\eta_p^2 = .40$ (see Figure 12 for vowel triangles). Thus, while mothers did not significantly hyperarticulate vowels to infants in the bilateral group (Table 6), the hyperarticulation index was significantly greater in the bilateral ($M = 1.62$, $SD = .89$) than in the unilateral group ($M = 0.37$, $SD = .40$), $p = .01$.

Table 6. *Results of one-sample t-test analyses (Cohen's d) comparing hyper-vowel and hyper-pitch scores to 1 (df=4 for unilateral group, df=9 for bilateral group) in IDS to infants with unilateral and bilateral HL*

Configuration	Hyper-vowels	Hyper-pitch
Unilateral	-3.53* (1.58)	5.42** (2.67)
Bilateral	2.21 (.70)	4.78** (1.50)

* $p = .02$, **$p = .01$

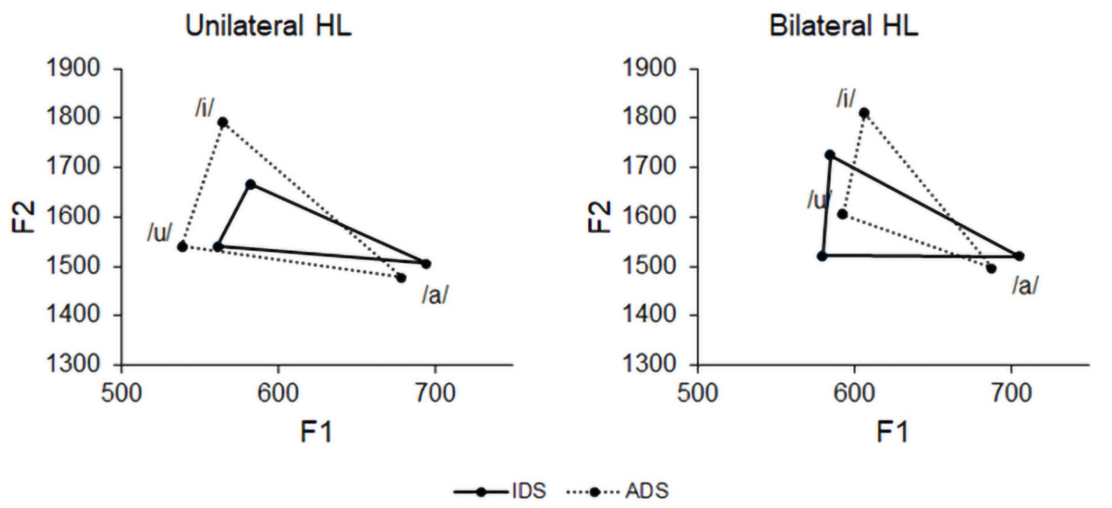

Figure 12. Vowel triangle areas for IDS and ADS for infants with unilateral and bilateral HL.

Pitch. Mothers produced exaggerated pitch in IDS to both groups of infants with HL, with no significant group effect ($F(1, 13) = .47$, $p = .50$, $\eta_p^2 = .04$).

3.4 Discussion

The main purpose of this study was to compare the acoustic features of IDS to infants with HL and with NH specifically focusing on exaggeration and variability in vowel production and pitch. In contrast to previous research, we have not found evidence for acoustic exaggeration of the three corner vowels /a, i, u/ in IDS manifested in their F1 and F2 values (Burnham et al., 2002; Kalashnikova et al., 2017; Kuhl et al., 1997; Uther et al., 2007). Furthermore, more global measures commonly used in previous research including vowel hyperarticulation, vowel space dispersion, and mean pitch height yielded no significant differences across groups. In fact, the degree of vowel hyperarticulation, an IDS component previously reported to be absent in IDS to infants with HL (Lam & Kitamura, 2010, 2012), was only moderated by infants' individual HL configuration whereby mothers reduced the space between the three corner vowels in their IDS to infants with unilateral but not bilateral HL. Each of these findings is discussed below.

3.4.1 Vowel hyperarticulation in IDS.

It is noteworthy that the results of this study revealed no evidence of vowel hyperarticulation in IDS to infants with NH confirming recent studies that suggest that this adjustment is not invariably manifested in all cases (Benders, 2013; Dodane & Al-Tamimi, 2007; Englund & Behne, 2005; Englund, 2018; Martin et al. 2015; Wong & Ng, 2018). However, it is contrary to previous studies reporting significant vowel hyperarticulation in IDS (Adriaans & Swingley, 2017; Cristia & Seidl, 2014; Kuhl et al., 1997; Tang et al., 2017; Uther et al., 2007), including findings for Australian English (Burnham et al., 2002; Kalashnikova & Burnham, 2018; Kalashnikova et al., 2017; Kalashnikova et al., 2018; Lam & Kitamura, 2010, 2012; Xu et al., 2013). It is possible that this absence of vowel hyperarticulation in IDS was driven by other factors that could influence individual formant values. Indeed, additional ANOVAs that compared mean F1 and F2 values for each vowel indicated lower F2 for /i/ in IDS compared to ADS ($F(1, 42) = 6.78$, $p < .05$, $\eta_p^2 = .14$). Also, an assessment of the F2-F1 distances for the vowel /i/ demonstrated closer F1 and F2 in IDS compared to ADS indicating less clear production of vowel /i/ in the IDS register. Since higher F2 for vowel /i/ reflects lip retraction characteristic of smiling in IDS (Benders, 2013; Fagel, 2010), lower F2 for /i/ in this experiment could have indicated that mothers were smiling less. This could have been driven by factors related to our experimental paradigm despite the fact that mothers were instructed to play with their infants naturally as they would at home, which are the same instructions used in previous studies. Therefore, while we failed to find vowel hyperarticulation in this experiment, it could be that this was driven by lower F2 for /i/, while F1 and F2 for other vowels did indicate vowel hyperarticulation. Moreover, it is quite possible that the wide age range in this experiment, necessitated by the availability of infants with HL and the requirement of both NH-CA and NH-HA control groups, influenced the findings.

3.4.2 Pitch height and pitch variation in IDS.

With regard to prosodic exaggeration in IDS, the results of this experiment demonstrated heightened pitch and greater pitch variability in IDS compared to ADS. This is in accordance with findings from previous studies that demonstrated heightened pitch and greater pitch variability in IDS compared to ADS (Fernald & Mazzie, 1991; Fernald & Simon, 1984; Grieser & Kuhl, 1988; Kalasnikova & Burnham, 2018). Given the evidence suggesting an important role of exaggerated pitch in IDS in attracting infants' attention to speech (Cooper & Aslin, 1990; Fernald & Simon, 1984) and enhancing speech processing (Graf Estes & Hurley, 2013; Ma et al., 2011; Thiessen et al., 2005; Trainor & Desjardins, 2002), these results indicate that infants with HL as well as both groups of infants with NH receive speech input with prosodic properties that are beneficial for their language acquisition.

3.4.3 Vowel hyperarticulation and pitch in IDS to infants with HL and NH.

No significant group differences were observed for the measures of vowel hyperarticulation or pitch in this study. While there are mixed findings in research on IDS to infants with HL, the results of this study are in line with studies that have not found consistent differences in vowel hyperarticulation (Wieland et al., 2015) and pitch (Bergeson et al., 2006; Lam & Kitamura, 2010; Miyamoto et al., 2005) as a function of infants' HL. However, there are studies that have found differences in IDS to infants with HL using these measures (Bergeson et al., 2006; Kondaurova, et al., 2012; Lam & Kitamura, 2010, 2012), but it must be noted that they differed from this study in testing infants prior to Cochlear Implantation, having smaller sample sizes, and using only chronological-age controls.

One factor that could have influenced these findings is that all infants in our sample received Cochlear Implants or Hearing Aids very early in life due to the practice of early intervention in Australia (Australian Hearing, 2011). However, we conducted *post-hoc* correlational analyses that demonstrated that the age of intervention did not have significant effects on vowel hyperarticulation (r = -.312, p = .324) or pitch (r = -.245, p = .444) although the moderate correlations were in the expected direction. Another important factor that could have attenuated potential effects of HL on IDS in this study is interventional therapy since all mother-infant dyads in our HL group were regularly attending behavioral speech therapy sessions. Speech therapy sessions and parent-directed interventions such as teaching parents language stimulation strategies, e.g., transparent labeling and linguistic mapping, may improve language development in infants with HL (Lund, 2018; Runnion & Gray, 2019) and thus may have an indirect effect on mothers' IDS qualities.

Other factors that may account for inconsistent findings in the literature on IDS to infants with HL, including this study, could include individual differences in the degree of HL and different hearing configuration within the samples of infants with HL. For instance, IDS to infants with Cochlear Implants has been reported to exhibit greater vowel hyperarticulation compared to infants with Hearing Aids (Wieland et al., 2015). The current sample of infants with HL included infants both with Cochlear Implants and Hearing Aids, but the comparison of these two groups showed no differences in IDS. This is not surprising given the small sample sizes. Nevertheless, even though the *t*-tests were not significant, it can be noted that numerically, scores were well above 1 for both hyper-vowels and hyper-pitch for infants with Hearing Aids but below 1 for infants with Cochlear Implants, which aligns with previously reported findings in these groups (Bergeson, 2011; Wieland et al., 2015). To the extent that these differences exist, they may account for disparities between studies. With respect to hearing configuration, the current study revealed differences in vowel hyperarticulation between infants with unilateral and bilateral HL. While there was vowel *hyper*articulation in IDS to infants with bilateral HL, vowels in IDS to infants with unilateral HL were *hypo*articulated. This could be due to different intervention approaches for infants with unilateral HL, which range from no treatment and regular monitoring, to the fitting of Hearing Aids and Bone Implant systems (Fitzpatrick et al., 2014). Also, it could be that later and more challenging fitting for infants with unilateral HL (Fitzpatrick et al., 2014) and different parental attitudes towards intervention (Fitzpatrick et al., 2015) could affect their IDS to these infants. To date, no previous studies have compared the properties of IDS to these two groups. However, this finding is not entirely surprising when viewed in the context of research showing that infants with unilateral HL have delayed vocabulary development and poorer auditory and language outcomes in comparison to infants with bilateral HL (Fitzpatrick et al., 2019; Välimaa et al., 2018).

3.4.4 Variability in vowel production.

The analyses in this Chapter included three measures of variability in vowel production: vowel space dispersion, formant dispersion, and F2-F1 distances. While we found no significant differences in vowel space dispersion between IDS and ADS, our measure of formant dispersion (Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013) indicated greater variability for F1 and F2 for vowel /a/ and F2 for vowel /i/ in IDS than in ADS. Although previous studies have demonstrated that the presence of variability may facilitate the acquisition of a number of early skills such as speech segmentation (Eaves, Feldman, Griffiths, & Shafto, 2016), and word learning (Galle, Apfelbaum, & McMurray, 2015; Graf Estes & Hurley, 2013; Rost & McMurray, 2009), it should be noted that different types of variability might play different roles in language acquisition. With respect to speech input, there are two main sources of variability: variability along specific phonetic dimensions (formants in this study), and variability in non-phonetic information (pitch in this study) (Rost & McMurray, 2009). Our finding regarding greater variability in IDS compared to ADS is consistent with other studies demonstrating that greater variability in IDS may potentially hinder category learning (Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). On the other hand, our findings demonstrate greater pitch variability in IDS compared to ADS. This finding is important since previous studies have shown that variability in non-phonetic information such as pitch enhances attention to speech and supports speech segmentation, and to some extent, vowel learning (Trainor et al., 2000). Therefore, our findings confirm that infants' exposure to IDS may play an important role in their language acquisition. Also, these findings suggest that different aspects of IDS may support language learning in different ways. However, it is still unknown how these components interact with each other and how they relate to infants' changing linguistic needs. However, the greater variability in vowel production reported in this Chapter demonstrates that it is possible that this is due to mothers' production of more variable speech. This would make vowels less clear and more difficult to learn, but it would keep their infants' attention to speech for longer, which may be what these infants need at this specific point in their development.

The third measure of vowel variability was F2-F1 distance for the corner vowels /a, i, u/ in IDS. Our results showed that the F2-F1 distance for the vowel /a/ was greater in IDS to infants with HL than to infants with NH matched by hearing age. Previous research on clear speech has found that as the separation between F1 and F2 for vowel /a/ increases, the less clear and less intelligible is the resulting speech (Ferguson & Kewley-Port, 2007; Smiljanić & Bradlow, 2009). This may be particularly relevant for the population with HL, since it is known that they rely on F1 properties to discriminate vowels (van Wieringen & Wouters, 1999). In this study, the greater F2-F1 distance for /a/ in IDS to infants with HL compared to infants with NH matched by hearing age could suggest that infants with HL receive less clear speech compared to infants with NH with the same amount of hearing experience.

3.4.5 Conclusion.

This Chapter investigated the features of IDS to infants with HL and infants with NH matched by chronological or by hearing age. Our findings showed that IDS to infants with HL has heightened pitch, as well as corner vowels that are acoustically exaggerated along two dimensions: the high-low dimension (F1) and the front-back dimension (F2). These adjustments were similar in IDS to infants with HL compared to IDS to infants with NH of the same chronological age and of the same hearing age. In addition, our findings indicate that the degree of vowel hyperarticulation in IDS differs as a result of differences in the configuration of HL with greater hyperarticulation in IDS to infants with bilateral than unilateral HL. These results support the view that IDS is characterised by acoustic components such as heightened pitch and higher formant frequencies, which may lead to infants' heightened attention to the speech stream and facilitated language acquisition. Furthermore, speech input to infants with HL appears to be very similar to that to infants with NH.

Since previous studies have demonstrated that IDS features change across development as a result of both infants' chronological age and linguistic needs (Kitamura & Burnham, 2003; Liu, Tsao, & Kuhl, 2009; Stern et al., 1983), the remaining question is whether the features found in this experiment would remain similar as infants acquire significantly more advanced vocabulary skills (18 months). Also, due to the wide age range of participants in this experiment, it is difficult to clearly assess whether and how mothers' IDS was adjusted to their infants' linguistic abilities. For this purpose, a longitudinal assessment targeting two specific ages (11 and 18 months) and relating IDS qualities to infants' lexical skills is necessary. Thus, the next Chapter will focus on a longitudinal assessment of the acoustic features in IDS to infants with HL. Given the previous findings demonstrating adjustments in IDS to infants with HL according to infants' hearing age (Kondaurova & Bergeson, 2011), in the next Chapter IDS to infants with HL will be compared to IDS directed to infants with NH matched by hearing age only. This will allow us to build on cross-sectional findings regarding the acoustic features of IDS to infants with HL and provide insight into potential modifications and stability of these features across infants' development.

CHAPTER 4

Developmental Changes to Acoustic Features in IDS to Infants with Hearing Loss

4.1 Introduction

Chapter 3 compared the acoustic features of IDS to infants with HL and to infants with NH matched by either chronological or hearing age. The specific focus of those comparisons was on the exaggeration and variability in vowel production and pitch in IDS. The findings indicated no significant group differences in vowel hyperarticulation and pitch, which is in line with a number of previous studies (Bergeson et al., 2006; Lam & Kitamura, 2010; Miyamoto et al., 2005; Wieland et al., 2015). On the other hand, findings from Chapter 3 suggest that IDS is qualified by greater variability in vowel production in IDS compared to ADS, regardless of infants' hearing status. Although previous studies have demonstrated that variability across phonetic dimensions may hinder category learning by making vowels less clear and more difficult to learn (Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013), it could be that this variability would keep infants' attention to speech for longer, which may be the infants' linguistic need specific for this stage in their development. Indeed, previous studies have shown that mothers modify their IDS features across infants' development not only according to infant age but also according to infants' changing linguistic needs. For example, it has been shown that IDS to younger infants consists of more exaggerated prosody due to infants' paying more attention to the affective information in speech (Kitamura & Burnham, 1998; Singh et al., 2002), while IDS to older infants consists of less exaggerated prosody but with clearer cues to linguistic structure in speech due to more mature linguistic abilities (Newman & Hussain, 2006). The remaining question is whether the acoustic features in IDS to infants with and without HL reported in Chapter 3 would remain stable as infants acquire more advanced vocabulary skills, marking a significant change in their linguistic abilities and needs (18 months). The aim of this Chapter is to longitudinally assess the effects of infants' age and changing linguistic needs on vowel and pitch production in IDS.

4.1.1 Developmental adjustment in IDS to infants with hearing loss.

As discussed in detail in Section 1.4.4, Chapter 1, adjustments to vowel production have been demonstrated to be stable in IDS to infants with NH, but adjustments to pitch vary as a function of infants' age (Benders, 2013; Kitamura & Burnham, 2003; Kitamura et al., 2001; Remick, 1976; Stern et al., 1983). Now, turning to IDS to infants with HL, longitudinal evidence is scarce. First, it should be noted that age is a complex construct when studying infants with HL. Specifically, in addition to chronological age, the hearing age of these infants reflects their amount of hearing experience, and it is calculated from the moment of hearing device activation. Although cross-sectional evidence suggests that mothers adjust their IDS to infants with HL according to infants' hearing experience rather than their chronological age (Bergeson et al., 2006; Kondaurova & Bergeson, 2011), very little attention has been paid to the developmental adjustments in vowel and pitch production in IDS to these infants. To date, only developmental changes in pitch production have been assessed demonstrating the absence of these changes over the 12-month period at three, six, and 12 months post-implantation (Kondaurova, Bergeson, & Xu, 2013). These findings are in contrast with documented prosodic modifications in IDS to infants with NH with three, six, and 12 months of chronological age (Kitamura & Burnham, 2003; Kitamura et al., 2001; Stern et al., 1983), which could be due to the later onset of modifications to prosodic characteristics in IDS to infants with HL as a result of differences in hearing experience. Given the importance of pitch for attracting infants' attention to speech and the potential linguistic role of vowel hyperarticulation, a longitudinal assessment of these features in IDS to infants with HL may clarify potential modifications of these features with infants acquiring more hearing experience and becoming older.

It should be noted that aside from the changing hearing experience of infants with HL, there are other possible sources of adjustment to maternal speech to these infants. One of these is interventional therapy including speech therapy sessions and parent-directed interventions such as transparent labelling and linguistic mapping (Lund, 2018; Runnion & Gray, 2019). Indeed, previous studies have demonstrated that participation in these interventional therapy sessions may improve infants' vocabulary growth and language development (Lund, 2018; Runnion & Gray, 2019). Thus, the interventional therapy may have indirect effects on mothers' IDS qualities.

A second potential factor is differential maternal experience in interacting with infants with HL. Meadow-Orlans (1997) demonstrated that mismatch in the communicative channel between mothers with NH and 12- and 18-month-old infants with HL negatively affects the quality of the mother-child interaction. However, further to the point made above, involvement in interventional therapies focused on teaching parents how to interact with infants with HL along with increased interactional experience as a function of infants' increasing age actually improve the quality of maternal interaction with infants with HL (Mohay, 2000).

The final possible source of adjustments in maternal IDS to infants with HL across development relates to infants' differential language abilities. Previous studies have indicated that mothers adjust their speech according to infants' language and speech processing abilities (Kalashnikova et al., 2018; Lam & Kitamura, 2012). For example, mothers do not hyperarticulate vowels in IDS to 11-month-old infants who are at risk for dyslexia and this appears to result from infants' language needs, as mothers' dyslexic status did not influence their IDS (Kalashnikova et al., 2018). While this study was conducted with NH infants, it is quite possible that that differential language abilities within the group of infants with HL may affect maternal adjustments to IDS across development.

4.1.2 Chapter aims and research questions.

In this Chapter, the acoustic features of IDS to infants with HL and infants with NH matched by hearing age were assessed longitudinally at two sessions conducted approximately six months apart. Only infants with NH who were of the same hearing age as infants with HL participated in this study. This is due to the fact that mothers of infants with HL adjust their speech according to infants' hearing age rather than chronological age, as demonstrated by results from Chapter 3 and previous studies (Bergeson et al., 2006; Kondaurova & Bergeson, 2011). Infants were first assessed around the age of 11 months and then again around the age of 18 months. These ages were chosen given that they mark important milestones in language development (Chapter 1, Sections 1.2.1.2 and 1.3.1). Between nine to 12 months infants develop native speech perception abilities, during which sensitivity increases to native-language consonant contrasts and decreases for non-native contrasts (Best et al., 1995; Best & McRoberts, 2003; Kuhl et al., 2006; Tsushima et al., 1994; Werker, 2003; Werker et al., 1981; Werker & Tees, 1983, 1984). Additionally, at around 12 months of age infants begin to say their first words, marking a developmentally significant age for language production. This age is also of interest because infants with NH have been shown to reduce their preference for IDS over ADS at this age (Hayashi et al., 2001; Newman & Hussain, 2006). The age of 18 months was chosen for the follow up session given that there is a significant increase in infants' expressive vocabulary skills between 18 and 24 months, accompanied by an increase in the speed and efficiency of word recognition (Fernald, 2000; Fernald et al., 2006). In other words, infants get better at recognising and interpreting the same word in more diverse and challenging contexts. Finally, infants' receptive and expressive vocabulary size was measured at the follow up assessment to study the possible relations between the acoustic features of maternal IDS and infants' emerging lexical abilities.

This experiment aimed to address the following research questions:

1. *Are acoustic exaggerations in vowel and pitch production manifested across development in IDS to infants with HL at 11 and 18 months of age?* On the basis of possible linguistic needs that infants may have at these ages, two alternative predictions were proposed separately for vowel and pitch production. With regard to pitch, if at both ages infants' linguistic needs consist of more attention to the speech stream, then we expect a similar degree of exaggeration in pitch production at both ages (Kondaurova et al., 2013). On the other hand, if as a result of acquiring more hearing experience infants have a reduced need for attention to speech, we expect less exaggeration in pitch production at the second age (Lam & Kitamura, 2010). With regard to vowel hyperarticulation, following the findings from Chapter 3, we expect vowel hyperarticulation to be absent in IDS to infants at the younger age. Additionally, if as a result of acquiring more hearing experience, older infants need clearer linguistic structure, we expect vowel hyperarticulation to be present at the older age (Wieland et al., 2015).
2. *Is IDS to infants with HL characterised by the same degree (amount) of variability in vowel and pitch production at 11- and 18-months of age?* In order to assess variability in vowel production, three different measures were adopted: vowel space dispersion, formant dispersion, and F2-F1 distances for corner vowels (/a, i, u/). If infants at both ages have similar attentional needs for speech, then we expect to observe a stability in vowel and pitch variability at both ages. On the other hand, if at the older age, infants would benefit from greater enhancement of vowel categories in order to learn words, then we expect the variability in terms of formant dispersion to decrease, while vowel

space dispersion and distances to increase for /i/ and /u/ and to decrease for /a/ (refer to Section 1.4.2.6, Chapter 1 for an explanation for the different predictions for each vowel).

3. *Is exaggeration in vowel production in IDS related to infants' vocabulary size?* Here, we predict that this relation will depend on the function that IDS may play in early language development. Thus, if IDS serves a linguistic function evident in the adjustment in vowel production, then we expect that measures of vowel production will be related to infants' vocabulary size (Kalashnikova & Burnham, 2018).
4. *Are there developmental changes to exaggeration and variation in vowel and pitch production in IDS to infants with NH?* In terms of developmental changes in vowel production, we predict a similar degree of vowel hyperarticulation in infants with NH at both 8 and 15 months of age (Kalashnikova & Burnham, 2018). In terms of variability in vowel production, it could be expected that if infants at each of these ages have similar attentional needs, then we expect to observe stable vowel and pitch variability across these ages. On the other hand, if at the older age, 15 months, infants benefit from greater enhancement of vowel categories in order to learn words, then we would expect the variability of *formant* dispersion to decrease over age, while *vowel space* dispersion and inter-formant distances to increase for /i/ and /u/ and to decrease for /a/ (Bradlow et al., 1996). Additionally, as we propose that these adjustments are specifically linguistic, we predict measures of pitch production to be stable across development (Kalashnikova & Burnham, 2018).

4.2 Method

4.2.1 Participants.

Two groups of mother-infant dyads participated in this longitudinal experiment. In the HL group, there were 11 dyads who completed two sessions approximately six months apart.

Infants' mean age at the first laboratory session was 10.52 months (*SD* = 2.18*, Age range* = 8.02 – 14.6) and 17.64 months (*SD* = 4.38, *Age range* = 11.77 – 27.94) at the second session (see Table 7 for further details). Infants with NH were matched by hearing age to the infants with HL. Eleven dyads participated in the first session (*Mean Age* = 8.09, *SD* = 2.25, *Age range* = 5.85 – 12.46) and nine dyads participated in the second session (*Mean Age* = 14.68, *SD* = 3.34, *Age range* = 10.16 – 18.74) (see Table 7 for further details). Two dyads that participated in the first session were not available for the second session due to moving out of the city (1) and being otherwise unable to come back to the lab (1). All mothers were native speakers of Australian English (*Mean age* = 33.32, *SD* = 3.40) and had normal hearing. All infants were monolingual, born full-term, and were not at-risk for any additional developmental disorders. Mothers' median education level was a University (bachelor) degree and a Kruskal Wallis H test showed that education level did not differ between the two groups ($\chi^2(1) = .98$, $p = .32$). Nine dyads in the group with HL and their corresponding hearing-age matched controls also had participated in the cross-sectional experiment reported in Chapter 3.

4.2.2 Procedure.

Mothers' speech was recorded in two types of situations: a play session with their infant (IDS) and a semi-structured interview with an adult experimenter (ADS). At the second session, only recordings of maternal IDS were obtained. Materials, equipment, and procedures were the same as in Chapter 3.

4.2.3 Measures.

The same measures as in Chapter 3 were used: vowel hyperarticulation, pitch, pitch variability and three measures of variability in vowel production: vowel space dispersion, formant dispersion, and F2-F1 distances. In order to obtain these measures from audio recordings, the same procedure was followed as in Chapter 3.

Table 7. *Infants' ages (months) at the Session 1 and Session 2 for infants with HL and infants with NH matched by hearing age (NH-HA)*

	Session 1		Session 2	
ID	HL	NH-HA	HL	NH-HA
1	9.20	7.72	18.87	17.62
3	9.40	6.67	12.85	10.16
4	14.60	6.80	27.94	/
7	12.06	7.13	19.20	/
8	8.28	5.85	15.42	12.98
12	11.83	9.76	17.59	15.06
13	8.02	6.42	14.17	12.36
18	9.80	7.56	19.92	17.75
22	11.93	11.87	17.19	17.16
23	12.52	12.46	19.17	18.74
24	8.09	6.77	11.77	10.26
Mean age	10.52	8.09	17.64	14.68

4.2.3.1 Vocabulary size.

During the second session, infants' caregivers completed the OZI: Australian English Communicative Development Inventory (Kalashnikova, Schwarz, & Burnham, 2016), which is the Australian English adaptation of the MCDI (Fenson et al., 1994). It is a checklist consisting of 558 words that may be familiar to infants and toddlers between 12 and 30 months of age. These words are organised into 15 semantic sections: "sound effects and animal sounds", "animals", "toys", "food and drink", "clothing", "body parts", "small household items", "furniture and rooms", "outside things", "places to go", "people", "games and routines", "action words", and "descriptive words". Additionally, the OZI contains sections for word forms, word endings, and mean length for the longest utterances that the child has produced (M3L). Caregivers were required to select the words that their child was able to understand (receptive vocabulary) and understand and say (expressive vocabulary). It has been showed that the OZI represents a reliable measure of vocabulary size for infants and toddlers acquiring Australian English (see Kalashnikova et al., 2016 for normative data and further details).

4.3 Results

The results are presented in three parts: acoustic features in IDS to infants with HL, acoustic features in IDS to infants with NH, and correlational analyses of IDS features and vocabulary scores. In the first two parts, the results are presented separately for vowel production and pitch production focusing on exaggeration and variability. In order to assess the exaggeration in both vowel and pitch production as well as variability in vowel production, hyper-scores for vowel hyperarticulation, vowel space dispersion, and pitch height were calculated by dividing each mother' IDS scores by her own corresponding ADS scores following the same procedure as in Chapter 3. This enables an estimation of *the degree to which each feature is exaggerated* in IDS compared to each mother's ADS. A score above 1 signifies *hyper*-articulation (expanded vowel triangle, more dispersed vowels, heightened pitch in IDS compared to ADS), a score below 1 signifies *hypo*-articulation (reduced vowel triangle, less dispersed vowels, reduced pitch compared to ADS), while a score of 1 signifies a production not different from ADS. After this, exploratory analyses were conducted on the hyper-scores for each variable in order to detect potential outliers. Infants whose hyper-scores were higher than three standard deviations from the mean have been excluded from the hyper-scores analyses. One-sample *t*-tests were used to compare each hyper-score to the value of 1 to determine whether hyper-scores were significantly > 1. In order to assess whether there was a difference in hyper-scores between the two sessions, linear mixed effects models (LMEs) were fitted using the *lmer* function of the *lme4* package (Bates, Maechler, & Bolker, 2013) in R (R core team, 2017). The dependent variable was Hyper-score, Session was included as the independent variable, and random intercept for Participants. These resulted in fitting three separate models:

Model 1 - vowel hyperarticulation: (Vowel hyperarticulation ~ Session + (1|Participants));

Model 2 - vowel space dispersion: (Vowel Dispersion ~ Session + (1|Participants));

Model 3 - pitch height: (Pitch Height ~ Session + (1|Participants)).

Next, to assess the variability in IDS across tokens for each corner vowel between the two sessions, three separate LMEs models were fitted. These models were fitted with F1, F2 or F2-F1 distance as the dependent variable, Session and Vowel as independent factors, and random intercept for Participants resulting in following models:

Model 4 – F1 variability: (F1_variability ~ Session * Vowel + (1|Participants));

Model 5 – F2 variability: (F2_variability ~ Session * Vowel + (1|Participants));

Model 6 – Distance: (F2-F1_Distance ~ Session * Vowel +(1|Participants)).

Pitch variability was assessed with the following LME model:

Model 7 – pitch variability: (Pitch Variability ~ Session + (1|Participants)).

The significance of each model was assess using ANOVAs with Satterthwaite's method using the *anova* function of the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017). In the cases where the models revealed significant effects, post-hoc analyses were conducted using the Tukey test from the *emmeans* package (Lenth, Singmann, Love, Buerkner, & Herve, 2019).

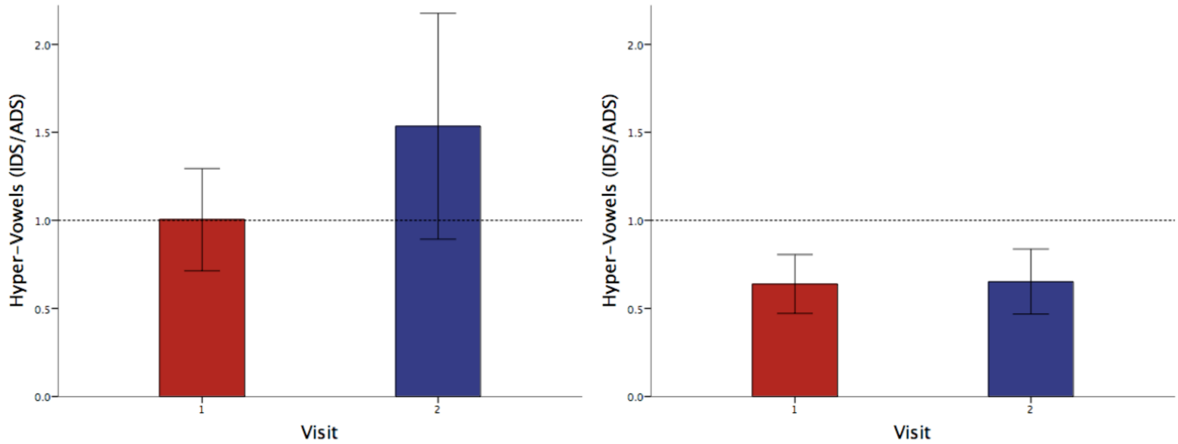

Figure 13. Hyper-scores for vowel articulation for infants with HL (left panel) and infants with NH (right panel) at both sessions (error bars represent SEM).

4.3.1 Infants with hearing loss.

Vowel hyperarticulation. One infant was identified as an outlier (hyper score was three standard deviations greater than the mean) and excluded from the vowel hyperarticulation analyses. The one-sample *t*-tests showed that during both sessions, mothers did not expand or reduce their vowel space compared to their ADS (Session 1: $t(9) = .02$, $p = .99$, *Cohen's d* = .01; Session 2: $t(9) = .83$, $p = .43$, *Cohen's d* = .26) (see Figure 13 for hyper-scores and Figure 15 for vowel triangles). The fitted model (Model 1) was not significant ($F(1, 18) = .56$, $p = .46$) suggesting no difference in the degree of vowel hyperarticulation between sessions.

Vowel space dispersion. Two infants were identified as outliers and have been excluded from vowel space dispersion analyses. One-sample *t*-tests demonstrated that at the first session, mothers produced vowels with less amount of dispersion in IDS compared to ADS ($t(8) = -2.48$, $p = .04$, *Cohen's d* = .82), and with a similar amount of dispersion in IDS compared to ADS at the second session ($t(8) = -.98$, $p = .36$, *Cohen's d* = .32) (see Figure 14 for hyper-scores). The fitted model (Model 2 – Vowel space dispersion) was not significant ($F(1, 8) = .64$, $p = .44$) suggesting that the amount of vowel space dispersion in IDS compared to ADS did not differ between the two sessions.

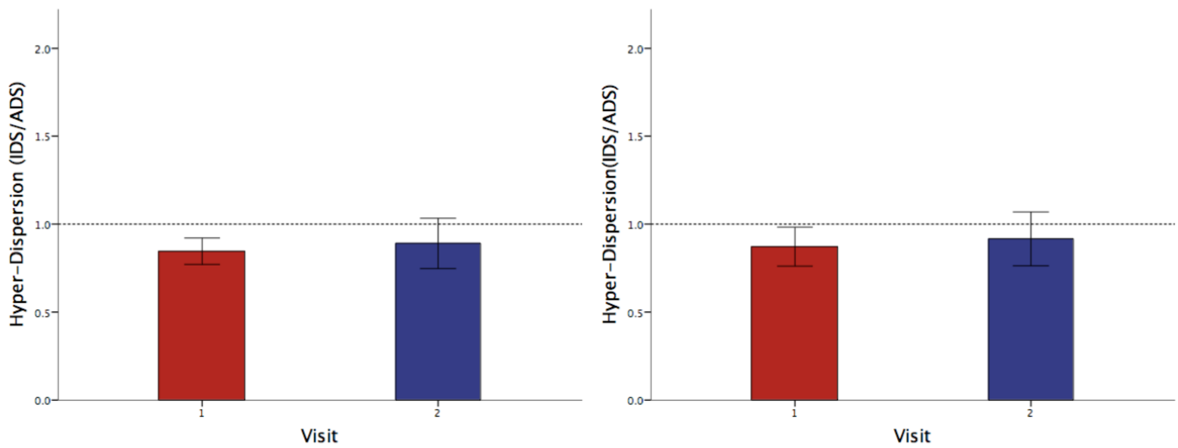

Figure 14. Hyper-scores for vowel space dispersion for infants with HL (left panel) and infants with NH (right panel) at both sessions (error bars represent SEM).

F1 dispersion. The LME results for F1 demonstrated that there was no significant main effect of Vowel ($F(2, 72) = 1.63$, $p = .20$), Session ($F(1, 72) = 2.26$, $p = .14$) and no significant Session by Vowel interaction ($F(2, 72) = .76$, $p = .47$).

F2 dispersion. As can be seen from Table 8, the fitted LME model for F2 (Model 5) revealed a significant main effect of Vowel ($F(2, 60) = 31.06$, $p < .001$). There was no significant main effect of Session ($F(1, 60) = .49$, $p = .49$) and no significant Session by Vowel interaction ($F(2, 60) = 1.23$, $p = .30$). The post hoc Tukey test demonstrated greater variability in the production of F2 for vowel /i/ ($M = 310$, $SE = 18.4$) compared to the vowels /a/ ($M = 131$, $SE = 18.4$), $p < .001$, and /u/ ($M = 202$, $SE = 18.4$), $p < .001$. Also, there was greater variability in the production of F2 for the vowel /u/ compared to the vowel /a/, $p = .01$.

Table 8. *Summary of the LME model fitted for the variability in F2 for the vowels /a, i, u/ for infants with HL*

Fixed effects	Estimate	SE	df	t value	p
Intercept	127.99	24.51	66.99	5.22	< .001
Session2	5.07	32.48	60.00	.16	= .88
Vowel2	177.22	32.48	60.00	5.46	< .001
Vowel3	101.24	32.48	60.00	3.12	= .01
Session2:Vowel2	5.06	45.93	60.00	.11	= .91
Session2:Vowel3	-59.60	45.93	60.00	-1.30	= .20
Random effects		Variance		SD	
Participants		995.5		30.91	

Table 9. *Summary of the LME model fitted for the F2-F1 distances for the vowels /a, i, u/ for infants with HL*

Fixed effects	Estimate	SE	df	t value	p
Intercept	794.82	25.60	32.43	31.05	< .001
Session2	9.94	30.62	586.32	.32	= .75
Vowel2	349.10	30.62	583.03	11.40	< .001
Vowel3	174.33	28.80	585.01	6.05	< .001
Session2:Vowel2	36.18	46.95	581.34	.77	= .44
Session2:Vowel3	-13.91	45.51	583.03	-.31	= .76
Random effects		Variance		SD	
Participants		3016		54.92	

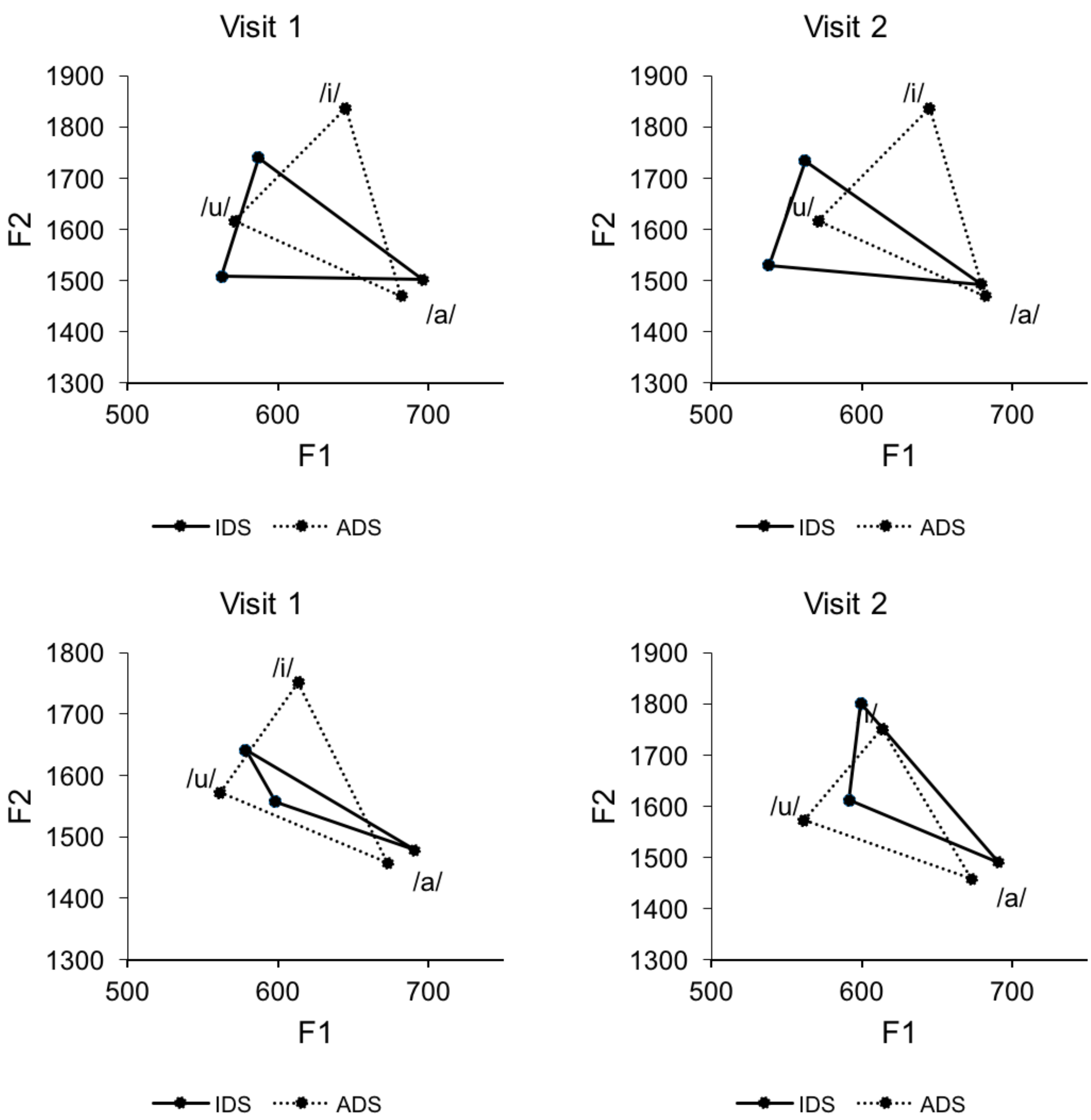

Figure 15. Vowel triangle areas for IDS and ADS for infants with HL (top panel) and infants with NH (bottom panel) at the first and second session.

F2 – F1 distances. The LME results demonstrated that there was a significant main effect of Vowel (F(2, 581.41) = 122.78, p < .001, but no significant main effect of Session (F(1, 586.68) = .77, p = .38), and no significant Session by Vowel interaction (F(2, 581.99) = .55, p = .58) (see Table 9 for the model summary). The post hoc Tukey tests showed greater distances between F1 and F2 for vowel /i/ (M = 1167, SE = 24.6) compared to both vowels /a/

(*M* = 800, *SE* = 22.4), $p < .001$, and /u/ (M = 967, SE = 23.9), $p < .001$. Also, there were greater distances between F1 and F2 for vowel /u/ compared to /a/, $p < .001$.

Pitch height. The *t*-tests showed that during both sessions, mothers significantly exaggerated pitch in IDS compared to ADS (Session 1: $t(10) = 9.31$, $p < .001$, *Cohen's d* = 2.67; Session 2: $t(10) = 8.28$, $p < 001$, *Cohen's d* = 2.67) (see Figure 16 for hyper-scores). The results of the LME model (Model 3 - pitch height) demonstrated no significant differences in maternal degree of pitch exaggeration between the two sessions ($F(1, 20) = .03$, $p = .87$).

Pitch variability. The fitted LME model for pitch variability (Model 7) failed to reach significance ($F(1, 10) = 2.24$, $p = .17$), suggesting that there was a similar amount in pitch variability across the two sessions.

Summary. These results show that there was no exaggeration in vowel production in IDS to infants with HL at both 11- and 18-months, and no significant difference between the two ages. The vowel space dispersion measure showed that IDS to infants around 11 months was less variable in relation to ADS, while at 18 months there was a similar degree of variability in IDS compared to ADS. The second measure of vowel variability, formant dispersion, demonstrated greater variability in the production of F2 for vowel /i/ compared to vowels /a/ and /u/ and greater variability for vowel /u/ compared to vowel /a/ with no difference in these measures at 11- and 18-months of age. The third measure of vowel variability, F2-F1 distances, demonstrated wider distances between F1 and F2 for vowels /i/ compared to vowels /a/ and /u/ and greater distances for vowel /u/ compared to vowel /a/ with no difference between the younger and older age.

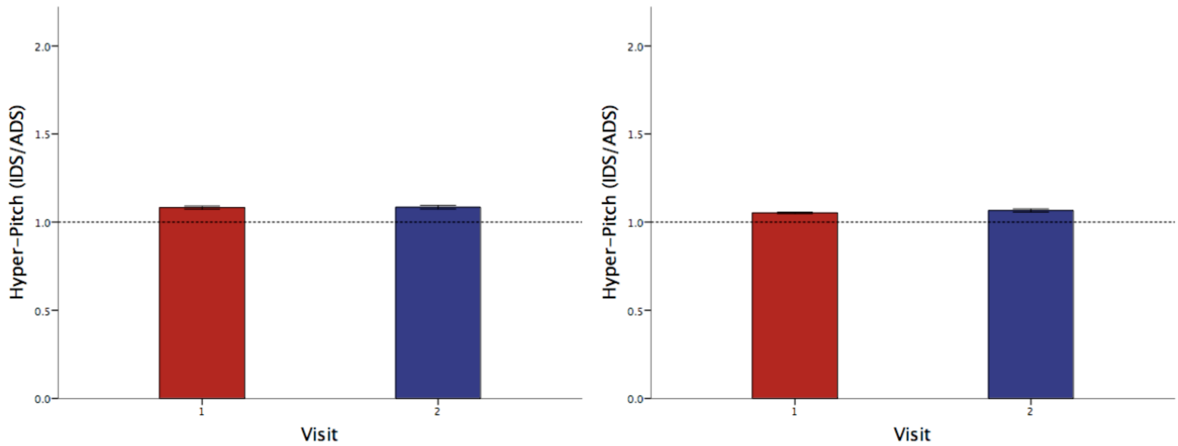

Figure 16. Hyper-scores for pitch height for infants with HL (left panel) and infants with NH (right right) at both sessions (error bars represent SEM).

With regard to pitch, these results indicate that mothers significantly exaggerated pitch height in IDS to infants with HL compared to ADS with no difference between the two ages. Also, these results suggest that there were similar amounts of variability in pitch production in IDS to infants with HL at both 11- and 18-months of age.

4.3.2 Infants with NH matched by hearing age.

Vowel hyperarticulation. Two infants were identified as outliers and have been excluded from vowel hyperarticulation analyses. One-sample *t*-tests were not significant showing that during both sessions mothers did not expanded the vowel space, however, the *t*-test for Session 1 approached significance in the opposite direction suggesting a reduction of vowel space in IDS compared to ADS (Session 1: $t(8) = -2.16$, $p = .06$, *Cohen's d* = .72; Session 2: $t(6) = -1.88$, $p = .11$, *Cohen's d* = .71) (see Figure 13 for hyper-scores and Figure 15 for vowel triangles). The fitted LME model (Model 1) was not significant ($F(1, 7.38) = .01$, $p = .94$) suggesting no significant difference in the degree of vowel hyperarticulation between the two sessions.

Vowel space dispersion. An exploratory analysis identified one infant as an outlier that was excluded from the vowel space dispersion analyses. The results of one-sample *t*-tests showed that during both sessions, mothers produced vowels with a similar amount of dispersion in IDS compared to ADS (Session 1: $t(9) = -1.16$, $p = .28$, *Cohen's d* = .37; Session 2: $t(7) = -.55$, $p = .60$, *Cohen's d* = .19) (see Figure 14 for hyper-scores). The fitted LME model (Model 2) was not significant ($F(1, 8.32) = .02$, $p = .89$) suggesting that there was a similar amount of vowel space dispersion between the sessions.

Table 10. *Summary of the LME model fitted for the variability in F1 for the vowels /a, i, u/ for infants with NH-HA*

Fixed effects	Estimate	SE	df	t value	p
Intercept	100.70	10.14	46.10	9.93	< .001
Session2	-21.68	14.53	40.77	-1.49	= .14
Vowel2	6.97	13.64	39.37	.51	= .61
Vowel3	-30.15	13.64	39.37	-2.21	= .03
Session2:Vowel2	-5.71	20.46	39.37	-.28	= .78
Session2:Vowel3	42.94	20.46	39.37	2.10	= .04
Random effects		Variance		SD	
Participants		98.06		9.90	

F1 dispersion. The LME results for F1 demonstrated no significant main effects for Vowel ($F(2, 39.37) = .82$, $p = .45$) and Session ($F(1, 43.31) = 1.20$, $p = .28$), but a significant Session by Vowel interaction ($F(2, 39.37) = 3.38$, $p = .04$) (see Table 10 for the model summary). The Tukey test revealed greater variability in the production of F1 for vowel /a/ at the first ($M = 100.7$, $SE = 10.1$) compared to the second session ($M = 79$, $SE = 11.4$), $p = .67$, greater variability in F1 for vowel /i/ at the first ($M = 107.7$, $SE = 10.1$) compared to the second session ($M = 80.3$, $SE = 11.4$), $p = .43$, and lower variability in F1 for vowel /u/ at the first ($M = 70.5$, $SE = 10.1$) compared to the second session ($M = 91.8$, $SE = 11.4$), $p = .69$.

Table 11. *Summary of the LME model fitted for the variability in F2 for the vowels /a, i, u/ for infants with NH-HA*

Fixed effects	Estimate	SE	df	t value	p
Intercept	129.70	19.30	53.76	6.72	< .001
Session2	-17.60	28.34	46.54	-.62	= .54
Vowel2	223.10	26.84	45.12	8.31	< .001
Vowel3	57.75	26.84	45.12	2.15	= .04
Session2:Vowel2	-27.67	40.02	45.12	-.69	= .49
Session2:Vowel3	5.81	40.02	45.12	.14	= .89
Random effects		Variance		SD	
Participants		134		11.58	

F2 dispersion. The results of the LME model (Model 5) showed a significant main effect of Vowel (F(2, 45.12) = 57.92, p < .001, but no significant main effect of Session (F(1, 49.15) = 2.30, p = .14), and no significant Session by Vowel interaction (F(2, 45.12) = .40, p = .67) (see Table 11 for the model summary). The Tukey tests demonstrated greater variability in the production of F2 for vowel /i/ (M = 331, SE = 15.3) compared to both /a/ (M = 119, SE = 15.3), p < .001 and /u/ (M = 186, SE = 15.3), p < .001, and greater variability in F2 for vowel /u/ compared to the vowel /a/, p = .01.

F2 – F1 distances. The results of the fitted LME model (Model 6) showed that there were significant main effects of Vowel (F(2, 662.67) = 181.38, p < .001, Session (F(1, 598.66) = 4.86, p = .03), and a significant Session by Vowel interaction (F(2, 660.21) = 4.46, p = .01) (see Table 12 for the model summary). The Tukey tests showed greater distances for /i/ (M = 1138, SE = 17.3) compared to /a/ (M = 789, SE = 16.9) and /u/ (M = 992, SE = 18), p < .001. Also, the distances for /u/ were greater than distances for /a/, p < .001. The main effect of

Session resulted from lower distances at the first (*M* = 955, *SE* = 15.2) compared to the second session (*M* = 990, *SE* = 16.2), $p = .03$, regardless of the vowel. The Tukey test demonstrated that the source of the interaction was a greater variability in distances between F1 and F2 for vowel /i/ at the first (*M* = 1090, *SE* = 21.2) compared to the second session (*M* = 1186, *SE* = 22.6), $p < .001$.

Table 12. *Summary of the LME model fitted for the F2-F1 distances for the vowels /a, i, u/ for infants with NH-HA*

Fixed effects	Estimate	SE	df	t value	p
Intercept	794.86	20.11	45.16	39.53	< .001
Session2	-11.90	25.89	664.47	-.46	= .65
Vowel2	294.97	24.63	661.99	11.98	< .001
Vowel3	185.89	25.44	664.88	7.31	< .001
Session2:Vowel2	107.62	36.63	658.76	2.94	= .01
Session2:Vowel3	33.88	37.86	660.73	.90	= .37
Random effects		Variance		SD	
Participants		1223		34.97	

Pitch height. One infant was detected as an outlier and was excluded from further analyses. The results of the *t*-tests showed that during both sessions, mothers significantly exaggerated pitch in IDS compared to ADS (Session 1: $t(10) = 8.85$, $p < .001$, *Cohen's d* = 2.59; Session 2: $t(8) = 8.21$, $p < 001$, *Cohen's d* = 3.50) (see Figure 16 for hyper-scores). The fitted LME model for pitch height (Model 3) indicated no significant difference in the degree of pitch height between the two sessions ($F(1, 9.15) = 2.50$, $p = .15$).

Pitch variability. The results of fitted LME model (Model 7) demonstrated no significant differences in pitch variability in IDS between the two sessions ($F(1, 8.65) = .21$, $p = .66$).

Summary. The results showed that there was no exaggeration in vowel production in IDS to infants with NH in both sessions. In terms of variability in vowel production, the vowel space dispersion measure showed comparable amounts of variability in IDS and ADS at both 8 and 15 months. The results for formant dispersion measures demonstrated that IDS to 8-month-old infants was characterised by greater variability in the production of F1 for vowels /i/ and /a/ compared to IDS to 15-month-olds. On the other hand, IDS to 8-month-olds contained less variability in the production of F1 for vowel /u/ as compared to IDS to 15-month-olds. Also, the results demonstrated greater variability in the production of F2 for vowel /i/ compared to vowels /a/ and /u/ and in the production of vowel /u/ compared to vowel /a/ regardless of infants' age. The third measure of vowel variability, F2-F1 distances, demonstrated a wider distance between F1 and F2 for vowel /i/ during the second compared to the first session indicating clearer production of this vowel in IDS to 15-month-old infants with NH. With regards to pitch production in IDS, there was an equivalent degree of hyper-pitch and pitch variability at 8- and 15-months of age.

4.3.3 IDS features and vocabulary size.

In order to assess whether IDS features were related to infants' vocabulary size, infants' receptive and expressive vocabularies were measured (see Table 13 for mean vocabulary scores). One-way analyses of covariance (ANCOVAs) were conducted to compare vocabulary scores between the two groups controlling for infants' age given that infants' chronological age in the HL and NH groups was different. The results of these analyses confirmed that infants' receptive vocabulary scores did not differ between the groups ($F(1, 17) = .76$, $p = .40$, $\eta_p^2 = .04$), with no significant effect of age on the receptive vocabulary ($F(1, 17) = 2.86$, $p =$

.11, $\eta_p^2 = .14$). Also, the expressive vocabulary scores did not differ between the groups ($F(1, 17) = 1.14$, $p = .30$, $\eta_p^2 = .06$). There was no significant effect of age on infants' expressive vocabulary scores ($F(1, 17) = .18$, $p = .67$, $\eta_p^2 = .01$). In order to assess whether IDS features were related to infants' vocabulary size, correlations between IDS measures that capture exaggeration in maternal speech at both sessions and vocabulary scores were assessed. These IDS measures included vowel hyperarticulation, vowel space dispersion, hyper-pitch, distances between F1 and F2 for vowels /a/, /i/, and /u/. For all assessed measures, partial correlations were conducted controlling for infants' chronological age. Additionally, similar partial correlational analyses were conducted separately for infants with HL and for infants with NH.

Table 13. *Mean receptive and expressive vocabulary scores for infants with HL and infants with NH at the second session*

Group	Receptive vocabulary	Expressive vocabulary
infants with HL	242.82 (174.06)	60.64 (105.54)
infants with NH	192.85 (150.28)	37.60 (81.26)

Table 14. *Pearson correlations (r) of IDS features at the first session and infants' receptive and expressive vocabulary scores at the second session*

	Hyper-vowels	Hyper-dispersion	Hyper -pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	.39	-.08	.25	.18	-.01	.22
Expressive	-.28	-.35	.18	-.22	-.05	.22

The results of the correlational analyses of IDS features at Session 1 and vocabulary scores at Session 2 are presented in Table 14. As Table 14 shows, no significant correlations were observed between these measures. Table 15 presents correlations of IDS features at Session 2 and vocabulary scores. As can be seen, there was a medium-sized correlation between receptive vocabulary size and vowel hyperarticulation, but it did not reach statistical significance. Moreover, a positive correlation was found between F2-F1 distances for vowel /i/ at the second session and receptive vocabulary size (r = .57, n = 17, p = .01). Also, there was a significant positive correlation between F2-F1 distances for the vowel /u/ at the second session and receptive vocabulary size (r = .60, n = 17, p = .01). These results suggest that infants whose mothers produced vowels /i/ and /u/ with wider distances between F1 and F2 at 15-18 months had larger receptive vocabulary sizes at this age.

Table 15. *Pearson correlations (r) of IDS features at the second session and infants' receptive and expressive vocabulary scores at the second session*

	Hyper-vowels	Hyper-dispersion	Hyper -pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	.44^	.24	-.09	.17	.57*	.60**
Expressive	.11	-.01	-.14	-.03	.16	.10

^ p = .09; * p = .02; ** p = .01

Table 16. *Pearson correlations (r) of IDS features to infants with HL in the first session with HL infants' receptive and expressive vocabulary scores in the second session*

	Hyper-vowels	Hyper-dispersion	Hyper -pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	.59	.42	.13	-.17	-.03	.28
Expressive	.33	-.44	.06	-.45	-.23	.23

The results of the correlational analyses of IDS features in Session 1 and *receptive and expressive* vocabulary scores of infants with HL at Session 2 are presented in Table 16 and show that there are no significant correlations. Table 17 presents correlations of IDS features in Session 2 and *receptive and expressive* vocabulary scores. As can be seen, there is a significant positive correlation between F2-F1 distances for the vowel /i/ at the second session and receptive vocabulary size (r = .66, n = 11, p = .04); a significant positive correlation between F2-F1 distances for the vowel /u/ at the second session and receptive vocabulary size (r = .64, n = 11, p = .01); and a significant positive correlation between degree of maternal vowel hyperarticulation in the second session and expressive vocabulary size at this session (r = .64, n = 11, p = .01). These results suggest that infants with HL whose mothers produced /i/ and /u/ vowels with wider distances between F1 and F2 at 18 months had larger receptive vocabulary sizes at this age. Additionally, these results indicate that infants with HL whose mothers produced IDS with more expanded vowels at 18 months had larger expressive vocabulary sizes at this age.

Table 17. *Pearson correlations (r) of IDS features to infants with HL, in the second session with HL infants' receptive and expressive vocabulary scores in the second session*

	Hyper-vowels	Hyper-dispersion	Hyper-pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	.50	.54	-.19	.26	.66*	.64^
Expressive	.81**	-.06	.43	-.19	.16	.11

^ p = .04, * p = .05, ** p = .01

Table 18. *For infants with NH, Pearson correlations (r) of IDS features in the first session with receptive and expressive vocabulary scores in the second session*

	Hyper-vowels	Hyper-dispersion	Hyper-pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	-.52	-.34	.62	-.44	-.08	.20
Expressive	-.57	-.60	.60	.04	.45	.57

Table 19. *For infants with NH, Pearson correlations (r) of IDS features in the second session with receptive and expressive vocabulary scores in the second session*

	Hyper-vowels	Hyper-dispersion	Hyper -pitch	F2-F1/a/	F2-F1/i/	F2-F1/u/
Receptive	.23	.29	.11	.02	.32	.60
Expressive	.01	-.42	-.06	-.15	.37	.40

Table 18 presents the results of the correlational analyses of IDS features at Session 1 and vocabulary scores of infants with NH at Session 2, while Table 19 presents correlations of IDS features at Session 2 and vocabulary scores. As these tables show, no significant correlations were observed between these measures.

4.4 Discussion

The main purpose of this study was to assess developmental adjustments in acoustic features of IDS to infants with HL as they acquire more hearing experience and to compare these to IDS to infants with NH matched by hearing age. Maternal IDS features were assessed when infants with HL were 11- and at 18-months-old and had eight and 15 months of hearing experience. These ages were chosen given the important milestones in language development that they mark. In assessing IDS features, the main focus was on exaggeration and variability in vowel production and pitch. The results demonstrated some differences in variability in vowel production between the two ages.

4.4.1 Developmental adjustments in vowel and pitch exaggeration in IDS to infants with hearing loss and infants with normal hearing.

The first research question in this study was whether acoustic exaggerations in vowel and pitch production are manifested in IDS to infants with HL at 11- and 18-months of age as they acquire more hearing experience. The results demonstrated an absence of vowel hyperarticulation in IDS to infants with HL at both the younger and older age. This is consistent with other studies that failed to show a presence of the vowel hyperarticulation component in IDS to infants with HL (Lam & Kitamura, 2010; 2012). The results are also consistent with those from Chapter 3. Similarly, the results demonstrated an absence of vowel hyperarticulation in IDS to infants with NH at both eight- and 15-months of age. This is also consistent with results from the cross-sectional experiment in Chapter 3. However, it is surprising that even at the lab session after six months, vowel hyperarticulation still was not present in IDS to these infants. The similar trend observed for vowel hyperarticulation in IDS to both groups of infants suggests that HL in infants does not affect maternal production of vowels in IDS as measured by vowel hyperarticulation. The absence of vowel hyperarticulation in IDS to both groups of infants may, although surprising, does not necessarily mean that mothers do not exaggerate vowels in IDS, it could be that the presence of vowel variability masked the vowel hyperarticulation measure. That is why an assessment of different aspects of vowel production may shed light on the extent of exaggerations in vowel production in IDS. Additionally, given the findings that the degree of vowel hyperarticulation is a result of infants' linguistic competence rather that their age (Kalashnikova & Burnham, 2018; Kalashnikova et al., 2018), these findings may suggest that at this stage mothers exaggerate other IDS features rather than the vowels due to specific linguistic needs infants may have.

Our findings that pitch height is exaggerated confirm these assumptions. Specifically, our findings demonstrated heightened pitch in IDS to both groups of infants compared to ADS. Also, results showed that heightened pitch in IDS was stable across infants' development. This confirms our assumption that infants at both ages still benefit from attentional properties of IDS evident in maternal production of this feature at both ages. Given the findings that infants with HL demonstrate reduced attention to the speech stream (Houston et al., 2003) and that their preference for IDS over ADS becomes evident after six months of device use (Robertson et al., 2013), it is possible that at the hearing age of around 13 months these infants still need input with features that attracts their attention to the speech stream. This is in accordance with previous studies with infants with NH that demonstrated exaggerated pitch height in IDS to infants during the second year (Benders, 2013; Kalashnikova & Burnham, 2018; Kitamura & Burnham, 2003; Kitamura et al., 2001). Additionally, the absence of a difference in pitch height in IDS to infants with HL and infants with NH matched by hearing experience suggests that hearing loss in infants does not affect pitch production in IDS.

4.4.2 Developmental adjustments in vowel and pitch variability in IDS to infants with hearing loss and infants with normal hearing.

The second research question we asked was whether IDS to infants with HL is characterised by more variability in vowel and pitch production as infants acquire more hearing experience. In answering this question, three different measures of vowel variability were employed. The first measure that we used was vowel space dispersion. Our findings demonstrated that IDS to infants with HL around 11 months was less variable in relation to ADS, while there was similar degree of vowel space dispersion in IDS compared to ADS at around 18 months. As greater vowel space dispersion in IDS compared to ADS results in vowel enhancement in IDS (Bradlow et al., 1996; Wieland et al., 2015), an observed increase in this measure at 18 months of age may suggest that mothers adjust their vowel production in IDS as infants gain more hearing experience. Although we have not observed greater vowel space dispersion in IDS compared to ADS at 18 months, it is possible that these infants are still at the stage where they need exaggerated attentional features in IDS. However, the increase in this feature across ages may suggest infants' transition to the stage where they need more exaggeration in IDS linguistic features. A similar trend was observed in infants with NH matched by hearing age, suggesting no effect of HL on vowel space dispersion in IDS. It is possible that mothers adjust their vowel production in IDS according to infants' hearing experience, thus, no difference between the two groups of infants was not found. Additionally, an observed increase in vowel dispersion in IDS compared to ADS over development may suggest clearer production of vowels over development related to infants' growing linguistic competence.

The second measure that we used to assess the variability in vowel production in IDS was formant dispersion. With regard to formant dispersion in IDS to infants with HL, the results demonstrated greater variability in production of individual vowels (i > u > a), but there was no difference between the two ages. With regard to infants with NH, results suggest that IDS to eight-month-old infants was characterised by greater variability in the production of F1 for vowels /i/ and /a/ compared to IDS to 15-month-olds. Since variability in the production of individual formants may result in vowel deterioration, these findings suggest that with increasing age and growing linguistic competence, vowels in IDS to infants with NH become clearer. However, the different trend in formant dispersion observed in IDS to infants with HL and infants with NH indicates that HL affects maternal production of vowels in IDS, specifically their production of the first and second formant frequencies.

Although variability in formants for individual vowels can result in vowel deterioration, it is important not only to assess variability in these formants but also distances between the first and second formant frequencies for each vowel. We have achieved this by using the F2-F1 distance measure for each vowel. This third measure of vowel variability demonstrated wider distances between F1 and F2 for vowels /i/ compared to vowels /a/ and /u/ and greater distances for vowel /u/ compared to vowel /a/ in IDS to infants with HL with no difference across development. The results for infants with NH matched by hearing age revealed a wider distance between F1 and F2 for vowel /i/ during the second compared to the first session indicating clearer production of this vowel in IDS to 15-month-old infants with NH compared to the younger age. Since wider distances between F1 and F2 for the vowel /i/ have been found to be correlated with overall speech intelligibility (Bradlow et al., 1996), our findings demonstrated enhancement in vowel production in infants with NH with increasing age. Additionally, the observed difference in this measure in IDS to infants with HL and infants with NH with the same amount of hearing experience further confirms our findings that there is a decrease in formant variability over development in IDS to infants with NH, that was not found in IDS to infants with HL. Overall, these findings indicate the influence of HL in infants on maternal production of formant frequencies. Given that the effect of HL on maternal production of vowels has not been observed in measures of vowel hyperarticulation and vowel space dispersion, these findings suggest that in assessing vowel production in IDS, a comprehensive approach with different measures of variability is needed.

Regarding variability in pitch production, our findings demonstrated no difference in pitch variability across development in IDS to both groups of infants, which is consistent with our findings regarding stability of pitch height across development. Therefore, it is possible that at these ages, infants receive speech input that has exaggerated pitch and pitch variability in order to attract their attention to the speech stream. Also, these findings confirm that HL in infants does not affect pitch production in IDS, which is in accordance with previous studies (Bergeson et al., 2006; Kondaurova & Bergeson, 2011).

4.4.3 Relation of the acoustic features in IDS to infants' vocabulary scores.

The analyses of the relations between IDS features and infants' vocabulary size demonstrated that infants whose mothers produced wider distances between F1 and F2 for vowels /i/ and /u/ at 15-18 months had larger receptive vocabulary sizes at this age. This is consistent with previous studies demonstrating that wider distances between F1 and F2 for vowels /i/ and /u/ are correlated with overall speech intelligibility (Bradlow et al., 1996). However, this is the first study to show that wider distances between F1 and F2 for vowels /i/

and /u/ in IDS to infants between 15 and 18 months of age are correlated with larger receptive vocabulary sizes at this age. This could be due to the greater speech clarity aiding infants' receptive vocabulary size. These findings add to previous findings regarding the relation of individual variability in maternal vowel production to infants' vocabulary size (Kalashnikova & Burhnam, 2018). Since distances between formant frequencies represent the precision of vowel realisation, these findings confirm a linguistic role of exaggeration and variability in vowel production for infants' lexical skills.

Additionally, correlational analyses conducted for each group separately demonstrated that infants with HL whose mothers produced wider distances between F1 and F2 for vowels /i/ and /u/ at 18 months had larger receptive vocabulary sizes at this age. This is consistent with previous studies with NH infants demonstrating the relation of the wider distances between F1 and F2 for vowels /i/ and /u/ with overall speech intelligibility (Bradlow et al., 1996). However, this is the first study to show that wider distances between F1 and F2 for vowels /i/ and /u/ in IDS to infants with HL at 18 months of age are correlated with larger receptive vocabulary sizes at this age. Moreover, the results here also show that infants with HL whose mothers produced vowels with a greater degree of vowel hyperarticulation at 18 months of age had larger expressive vocabulary sizes at this age. Thus, this study shows that the positive relationship between maternal vowel hyperarticulation in IDS and infants' expressive vocabulary size is not restricted NH infants (Kalashnikova & Burhnam, 2018), but also holds for infants with HL.

Additionally, our results demonstrated that these relations between formant distances in maternal IDS and infants' receptive and expressive vocabularies do not change as a function of age, but rather are related to infants' vocabulary. This suggests that vowel production in maternal IDS is modulated in response to infants' language development and specific needs that they may have. Given that our results demonstrated that the production of vowels in IDS is affected by HL in infants, this finding may indicate that the receptive and expressive vocabularies of infants with HL may be affected as well. However, a closer look into infants' receptive and expressive vocabularies disputes this assumption since there was no significant difference in receptive and expressive vocabularies between infants with HL and NH. This suggests that infants with HL may utilise different cues from infants with NH in order to build their vocabularies.

4.4.4 Conclusion.

This study longitudinally assessed the acoustic features of IDS to infants with HL and to infants with NH matched by hearing age with these infants. The findings demonstrated a stability in vowel hyperarticulation, pitch height, and pitch variability across the two ages in IDS to both groups of infants. However, it should be noted that there are some issues that could affect the results of this experiment. First, the sample sizes for both infants with HL and NH are small. Additionally, there is a wide heterogeneity in the sample with HL including infants with both unilateral and bilateral HL as well as infants fitted with different types of hearing devices. As demonstrated by the exploratory analyses in Chapter 3, the vowel hyperarticulation patterns may have varied across these sub-groups of infants with HL.

Importantly, the results of this experiment suggest that HL may have an effect on maternal IDS even when infants' hearing experience is controlled. Specifically, the results showed that whereas in IDS to infants with NH variability in formant dispersion decreased when these infants became older, there was no difference in formant variability for infants with HL between the two testing sessions. Also, while distances between F1 and F2 for vowel /i/ were wider at the older age in IDS to infants with NH, there was no difference for infants with HL. These findings suggest that HL in infants affects maternal production of formants in IDS. Furthermore, the results of this experiment showed a relation among the distances between F1 and F2 for corner vowels /i/ and /u/ and infants' receptive vocabulary size suggesting that infants whose mothers produce vowels with wider distances between F1 and F2 have larger receptive vocabularies. This finding supports the importance of vowel production in IDS for infants' receptive vocabulary skills.

Chapters 3 and 4 focused on analysing the measures of vowel and pitch production in natural IDS produced by mothers of infants with HL and infants with NH matched by chronological or hearing age. The results indicated a relation between IDS features and infant vocabulary suggesting that IDS features play a linguistic role in infants' language acquisition. However, it is unclear what exact mechanisms underlie this relation. Based on previous research, it is possible that exposure to speech carrying the specific acoustic features of IDS facilitates early linguistic processing (Kalashnikova, Peter, Di Liberto, Lalor, & Burnham, 2018), fostering infants' ability to encode and process linguistic units such as phonemes and words (Peter et al., 2016; Song et al., 2010; Zhang et al., 2011). Since these features tend to co-occur in IDS, it is hard to determine their potential role in infants' language processing. In order to obtain a complete picture about the role of IDS features in language processing, direct assessments are needed. One way to achieve this is by manipulating the presence of these features in IDS and assessing its effects on infants' lexical processing performance. In the next Chapter, this is achieved by manipulating the presence and absence of vowel hyperarticulation and pitch in IDS and ADS to assess their role in 18-month-old infants' lexical access and recognition of lexical forms. Additionally, it should be noted that in the experiments described in the next two Chapters (Chapters 5 and 6) lexical processing was assessed in infants with NH since we aimed to obtain a complete picture of the potential roles of specific IDS features to better understand their presence in natural IDS. Thus, assessment of their effect in infants without impairment in auditory or sensory processing is needed.

CHAPTER 5

The Role of the Acoustic Features of IDS in Lexical Processing at the Behavioural Level

5.1 Introduction

Chapters 3 and 4 assessed the acoustic features in natural IDS to infants with HL and two groups of infants with NH. The results of these chapters demonstrated the presence and stability of some features across infant development (pitch height and variability) and the absence of some features (vowel hyperarticulation and vowel space dispersion). Importantly, findings from Chapter 4 indicated a relation between vowel formant distances in IDS and infants' receptive vocabulary skill supporting the linguistic role of IDS in infant language acquisition. Given that the experiments in Chapters 3 and 4 demonstrated the presence and stability of pitch in IDS over development, but an absence of vowel hyperarticulation, this raises the question whether the pitch is enough to facilitate lexical processes or vowel hyperarticulation is also needed. Since these acoustic features typically co-occur in natural speech, it is hard to tease apart their potential roles in infants' online language processing. Thus, direct assessments of the effects that these features may have on lexical processing is needed. The ideal way to do this is by manipulating the presence of these features in IDS and assessing its effects on infants' lexical processing performance. Since previous studies (Graf Estes & Hurley, 2013; Kalashnikova & Burnham, 2018; Ma et al., 2011; Thiessen et al., 2005; Trainor & Desjardins, 2002) demonstrated the facilitative role of vowel hyperarticulation and pitch in IDS, the focus here is on these two features and their role in lexical processing. Therefore, the goal of this Chapter is to assess the role of vowel hyperarticulation and exaggerated pitch in lexical processing in 18-month-old infants by manipulating the presence of these features in IDS and ADS.

5.1.1 The debate on the roles of the specific IDS features.

As already described in Chapter 1, Section 1.4.2.5, there is a debate in IDS research regarding the potential linguistic role of the vowel hyperarticulation component in IDS (Cristia, 2013). To address this debate, this experiment focused specifically on the roles that exaggerated prosody and vowel hyperarticulation may play in facilitating early lexical development. These two IDS features were chosen given the evidence on their facilitative roles in infants' language acquisition (Graf Estes & Hurley, 2013; Kalashnikova & Burnham, 2018; Ma et al., 2011; Thiessen et al., 2005; Trainor & Desjardins, 2002). Only one study to date has investigated this question. Specifically, Song and colleagues (2010) assessed how slow speaking rate, vowel hyperarticulation, and wide pitch range in IDS impact lexical processing in 19-month-old infants. They employed the Looking-While-Listening task (LWL, Fernald et al., 2008) that will be discussed in detail in Section 5.1.2. In this study, infants' performance was compared in *typical*-IDS with performance in each of the following three modified-IDS conditions*:* (i) *fast*-IDS that lacked the slow speaking rate, (ii) *hypo*-articulated-IDS that lacked the hyperarticulated vowels, and (iii) *monotonous*-IDS that lacked the wide pitch range. These comparisons demonstrated that slower speaking rate significantly improved infants' lexical processing accuracy and latency. Also, the *typical*-IDS condition yielded shorter response latencies compared to the *hypo*-IDS condition suggesting a potentially facilitative role for vowel hyperarticulation. However, the *typical*-IDS condition in this study consisted of combined vowel hyperarticulation and exaggerated prosody components. Thus, it is difficult to determine whether clarity cues alone (vowel hyperarticulation) would be sufficient to facilitate infants' lexical processing, or whether the combination of attentional (pitch, pitch range) and clarity cues is required. Thus, the question remains as to whether vowel hyperarticulation facilitates lexical processing independently of exaggerated prosody. Manipulating the presence and absence of a particular feature in both IDS and ADS may provide some answers.

A recent study (van der Feest, Blanco, & Smiljanic, 2019) might clarify this issue to some extent. Van der Feest and colleagues (2019) assessed adults' word recognition in response to three different listener-oriented speaking styles: clear speech (ADS with *hyper*articulated vowels), natural IDS (IDS with *hyper*articulated vowels), and conversational speech (ADS with *hypo*articulated vowels). Results showed that clear speech and IDS facilitated adults' word recognition. In this case, the clear speech condition contained hyperarticulated vowels without any other acoustic properties of IDS. These findings suggest that this component may make a contribution independently from other IDS features to facilitating lexical processing. However, it remains unclear whether a similar effect would be observed in young infants.

5.1.2 The Looking-While-Listening procedure.

The Looking-While-Listening procedure (LWL, Fernald et al., 2008) is a widely used procedure for evaluating lexical processing abilities. In infancy research, Fernald and colleagues (1998) were the first to use this procedure for assessing infants' lexical processing. The LWL procedure consists of presenting two visual stimuli to the infant, as well as an auditory stimulus (a spoken word) that matches one of the visual stimuli. It measures the speed and accuracy of matching the spoken word with a visual representation of that word. For example, an infant may be presented with the images of a car and a shoe side by side and with the auditory stimulus "Where is the *shoe*?". Thus, it is expected that the infant's eye gaze pattern towards the matching image will reflect infant's understanding of this particular word. One of the advantages of this procedure lies in providing a moment-by-moment measure of speech processing, thus, allowing the coding of response latencies on multiple trials, over multiple items, and with millisecond precision (Fernald et al., 2008).

5.1.3 Chapter aims and research questions.

This experiment manipulated the presence and absence of vowel hyperarticulation in IDS and ADS to assess 18-month-old infants' lexical access and recognition of lexical forms. This age was selected given that it marks the time when infants' expressive vocabulary undergoes significant growth, but also when there is a significant increase in their word-recognition speed and efficiency (Fernald, 2000; Fernald et al., 2006). Using the eye tracking, the LWL paradigm (Fernald et al., 2008) was employed to measure infants' accuracy and latency in recognising the visual referent of a familiar word in real time. Three between-subjects conditions were created: *hyper-IDS*, *non-hyper-IDS*, and *hyper*-ADS. In the *hyper*-IDS condition, speech consisted of acoustic exaggerations typical of natural IDS such as slower speaking rate, higher pitch, wider pitch range, and hyperarticulated vowels (*clarity and attentional cues combined*). The *non-hyper*-IDS condition consisted of acoustic exaggerations typical of natural IDS, but the vowel hyperarticulation feature was absent (*attentional cues only*). The *hyper*-ADS condition employed only one acoustic exaggeration from IDS, vowel hyperarticulation, while all other features were typical of ADS (faster speech rate, lower pitch, reduced pitch range, *only the clarity component*).

Two alternative predictions were constructed. First, if exaggerated prosody in IDS facilitates lexical processing, then greater accuracy and shorter latencies were expected in the two conditions with exaggerated pitch (*hyper*-IDS, *non-hyper*-IDS) compared to the condition without exaggerated pitch (*hyper*-ADS) (Graf Estes & Hurley, 2013; Thiessen et al., 2005). Alternatively, if vowel hyperarticulation facilitates lexical processing, then greater accuracy and shorter latencies were expected in the two conditions with vowel hyperarticulation (*hyper*-

IDS, *hyper*-ADS) compared to the condition without vowel hyperarticulation (*non-hyper*-IDS) (Song et al., 2010).

5.2 Method

5.2.1 Participants.

Sixty (28 female) full-term born monolingual Australian English-learning 18-month-old infants participated. All infants had normal hearing and vision. Twenty infants were randomly assigned to one of the three following conditions: *hype*r-IDS (*Mean age* = 18.68, *SD* = .758, *Age range* = 17.82 - 20.71 months), *non-hyper*-IDS (*Mean age* = 18.47, *SD* = .600, *Age range* = 17.59 - 19.59 months), and *hyper*-ADS (*M*ean age = 18.81, *SD* = .823, *Age range* = 17.75 - 20.39). Infants' age did not differ across the three conditions ($F(2, 57) = 1.14$, $p = .33$, $\eta_p^2 = .04$). An additional 11 infants were tested but excluded because they were bilingual (1), failed to capture sufficient gaze data (5), extreme fussiness (4), and equipment failure (1).

5.2.2 Stimuli and Apparatus.

The audio stimuli consisted of six words (book, car, cup, key, sheep, shoe) embedded in two carrier phrases: "Where is the *target*?" and "Look at the *target*!". Visual stimuli were images of pairs of objects depicting the target words, approximately 13cm in height and separated by about 18cm.

A female native speaker of Australian English was recorded producing the stimuli. The speaker produced all stimuli without addressing an interlocutor, but she followed specific instructions for each experimental condition. She was instructed: (i) to imagine that she was addressing an infant (*hyper*-IDS), (ii) to imagine that she was addressing an infant but to produce vowels less clearly (*non-hyper*-IDS), (iii) to imagine that she was addressing someone who could not hear her well, so she had to speak clearly, over-enunciating the words (Lam, Tjaden, & Wilding, 2012) (*hyper*-ADS). The recorded phrases were subject to acoustic analyses (F1, F2, F0) in Praat (Boersma & Weenink, 1996), and the best instances according to the specifications for each condition were chosen. The acoustic details of all the stimuli used in the task are available in Appendix C.

To ensure that the productions indeed met the goals of the intended speech styles (*hyper*-IDS > (*non-hyper*-IDS = *hyper*-ADS)), pitch height and range were compared. With regard to *pitch height*, a univariate ANOVA confirmed a significant difference across conditions ($F(2, 33) = 9.42$, $p < .01$, $\eta_p^2 = .36$). Post-hoc Bonferroni comparisons demonstrated greater pitch height in *hyper*-IDS (M = 314.02 Hz, SD = 45.82) compared to both *non-hyper*-IDS (M = 226.12 Hz, SD = 67.42), $p < .01$, and the *hyper*-ADS conditions (M = 249.72 Hz, SD = 35.60), $p < .05$. Pitch height did not differ significantly between non-*hyper*-IDS and *hyper*-ADS conditions, $p = .80$. With regard to *pitch range*, a univariate ANOVA confirmed a significant difference across conditions ($F(2, 33) = 7.98$, $p < .01$, $\eta_p^2 = .33$). Post-hoc Bonferroni comparisons demonstrated greater pitch range in *hyper*-IDS (M = 251.30 Hz, SD = 45.82) compared to the *non-hyper*-IDS condition (M = 113.84 Hz, SD = 67.42), $p < .01$. Pitch range did not differ significantly between *hyper*-IDS and *hyper*-ADS conditions (M = 190.15 Hz, SD = 67.42), p =.26. Also, pitch range did not differ significantly between non-*hyper*-IDS and *hyper*-ADS conditions, p =.10.

Additionally, in order to ensure that vowel hyperarticulation was greater in hyperarticulation conditions (*hyper*-IDS, *hyper*-ADS) compared to *non-hyper*-IDS condition, a one-way ANOVA was conducted. The one-way ANOVA showed that there was a significant difference in vowel space area across conditions ($F(2, 33) = 1.327E+33$, $p < .001$). The degree of vowel space area was the greater in *hyper*-ADS (M = 482006.39 Hz^2) compared to both *non-hyper*-IDS (M = 58356.02 Hz^2) and *hyper*-IDS (M = 88981.04 Hz^2), $p < .001$. The degree of vowel space area was greater in *hyper*-IDS compared to non-*hyper*-IDS condition, $p < .001$.

Visual stimuli were presented on a 22-inch screen using a Tobii-X120 eyetracker and Tobii Studio software to collect eye-movement data (120-Hz sampling rate). The audio stimuli were delivered through two forward-facing loudspeakers positioned below the screen.

Figure 17 presents the structure of a sample LWL trial. The task consisted of 24 trials subdivided into 4 blocks (three trials using each of the carrier phrases) (Swingley & Aslin, 2000). The target image appeared three times on each side within each block. Two stimulus orders were created with each image presented as both the target and distracter four times. Between the blocks, filler trials were presented to maintain infants' interest.

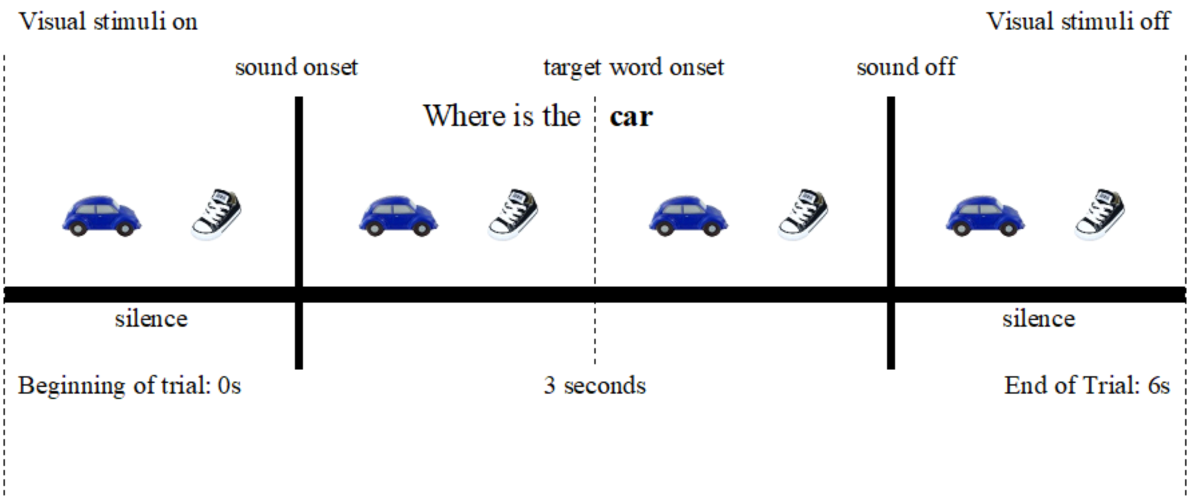

Figure 17. Example of an experimental LWL trial.

5.2.3 Procedure.

Infants sat on their caregiver's lap in a dimly lit soundproof laboratory room, approximately 60cm away from the screen. Caregivers listened to masking sounds over noise-cancelling headphones and were instructed to look away from the screen to prevent their gaze from interfering with the eye-tracker's recording. At the beginning of the experiment, a five-point infant calibration routine was completed. Before each trial, an attention-getter stimulus was presented. The experimenter observed the infant from an adjoining room and controlled the trial presentation, so that each LWL trial started when the infant fixated the centre of the screen. In order to obtain infants' receptive and expressive vocabulary scores, after the LWL tasks, infants' caregivers completed the OZI (Kalashnikova et al., 2016; see Chapter 4, Section 4.2.3 for more details on the OZI).

5.2.4 Processing of Eye-Tracking data.

Data for infants who provided less than 40% of gaze throughout the task were excluded prior to analyses (five infants, see Section 5.2.1). The EyetrackingR package (Dink & Ferguson, 2015) in R (R Core Team, 2017) was used to process the eye-tracking data. First, two areas of interest (AOI) were defined encompassing the image of each object. Next, the time-window from 300ms after the target word onset (to account for the time needed to process the auditory stimulus and to initiate an eye movement) to 1800ms was analysed, resulting in a 1500ms time-window (Marchman & Fernald, 2008). Next, we calculated the amount of track loss in each trial removing the trials with over 25% track loss (721 trials in total). Finally, the proportion of the accurate looks to the target object (accuracy) and latency of the first look to the target object were calculated to be used as dependent variables in statistical analyses.

5.3 Results

Figure 18 depicts the time course of infants' looking to the target object in the *hyper*-IDS, *non-hyper*-IDS, and *hyper*-ADS conditions. In order to assess infants' accuracy and latency, two types of analyses were conducted: a window analysis (accuracy in the critical test window), and an onset contingent analysis (response latency).

5.3.1 Accuracy.

Accuracy refers to the proportion of fixation to the target object in response to hearing the target label out of the total fixation time to the target and the distracter. Infants in the *hyper*-IDS and *non-hyper*-IDS conditions showed above-chance looking (chance = .5) to the target object indicating recognition of the target words, while this was not the case in the *hyper-ADS* condition (see Table 16, *p*-values were adjusted to .016 using the Bonferroni correction for multiple comparisons). To compare infants' response accuracy across conditions, a univariate Analysis of Variance (ANOVA) with Mean Accuracy as the dependent variable and Condition as the factor was conducted, but it showed no main effect of Condition ($F(2, 39) = .27$, $p = .77$, $\eta_p^2 = .01$).

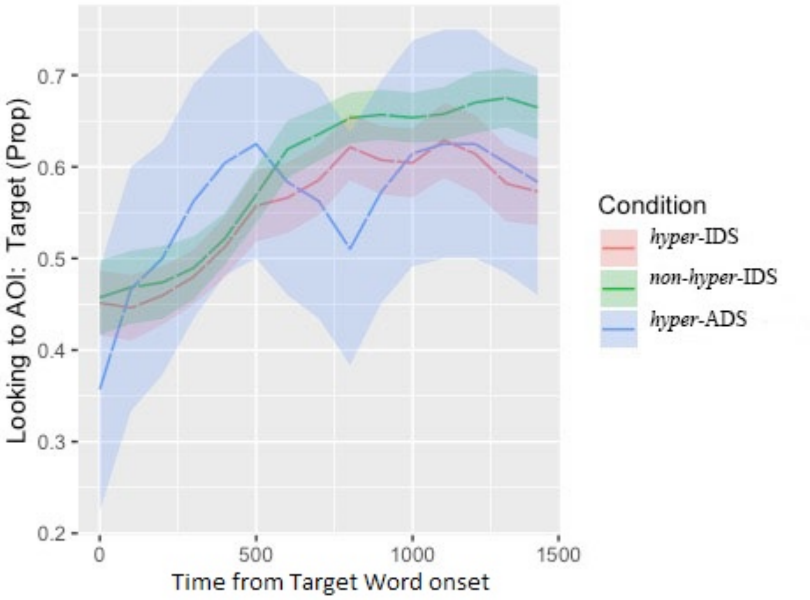

Figure 18. Time course of infants' proportion of looking to the target object in the three experimental conditions.

5.3.2 Latency.

To assess how quickly infants switched their looking to the target object when hearing the target label, an onset contingent analysis was conducted. This analysis distinguishes between two types of trials. *Target-initial trials*, in which infants were looking at the target object at the target-label onset and *Distracter-initial* trials, in which infants were looking at the distracter object at the target-label onset. Only the *Distracter-initial* trials were of interest here (see Figure 19) since latency represents the speed of the shifts in looking away from the distracter towards the target object in response to the target label (Fernald et al., 2008).

Table 20. *Results of one-sample t-test analyses comparing the proportion of looking to the target object against chance (0.5) in the three conditions*

Condition	Mean (SD)	t	df	Cohen's *d*
hyper-IDS	.57 (.08)	3.73*	18	.86
non-hyper-IDS	.57 (.08)	3.93**	18	.90
hyper-ADS	.54 (.37)	.43	16	.10

*p = .01; **p < .001

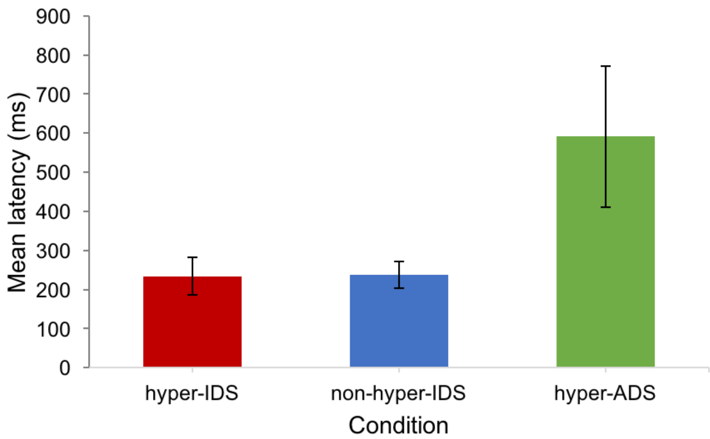

Figure 19. Mean response latency (ms) for Distracter-Initial trials across the three conditions

To compare latency across conditions, we conducted a univariate ANOVA with Mean Latency as the dependent variable and Condition as the factor, which yielded a significant main effect of Condition ($F(2, 39) = 6.15$, $p = .01$, $\eta_p^2 = .24$). Planned pairwise Bonferroni comparisons demonstrated that infants' responses were significantly faster in the *hyper*-IDS ($M = 233.65$, $SD = 196.79$) than the *hyper*-ADS ($M = 591.43$, $SD = 477.40$) condition, $p = .01$, and in the *non-hyper*-IDS (M = 237.06, SD = 145.11) than the *hyper*-ADS (M = 591.43, SD = 477.40) condition, p = .01. No significant difference emerged between the *hyper*-IDS and *non-hyper*-IDS conditions, p = 1.00. Thus, while there was no difference in latency between the two IDS conditions, infants in the *hyper*-ADS condition were the slowest in switching their looks to the target object.

5.3.3 Vocabulary size and performance on the lexical processing task.

To assess whether infants' language knowledge affected lexical processing performance, infants' receptive and expressive vocabularies were assessed (see Table 17 for mean vocabulary scores). Univariate ANOVAs confirmed that infants' receptive (F(2, 57) = .62, p = .54, η_p^2 = .02) and expressive vocabulary scores did not differ across the three conditions (F(2, 57) = .29, p = .75, η_p^2 = .01).

Table 21. *Mean (SD) receptive and expressive vocabulary scores for infants in hyper-IDS, non-hyper-IDS, and hyper-ADS conditions*

Condition	Receptive vocabulary	Expressive vocabulary
hyper-IDS	238.5 (117.77)	109 (119.6)
non-hyper-IDS	2332.65 (115.69)	87.9 (80.7)
hyper-ADS	268.85 (95.02)	92.05 (73.71)

Next, the correlations between infants' vocabulary scores and accuracy and latency measures in the LWL task were assessed (see Table 18). As can be seen, in the *hyper*-ADS condition infants with larger receptive vocabularies achieved greater accuracy, and infants with both larger receptive and expressive vocabularies achieved shorter latencies. Furthermore, in the *non-hyper*-IDS condition infants with larger receptive vocabularies achieved shorter latencies. In the *hype*r-IDS condition, there were no statistically significant correlations.

Table 22. *Pearson correlations (r) of infants' latency and accuracy measures and receptive and expressive vocabulary scores in the three conditions*

Condition	receptive-accuracy	receptive-latency	expressive-accuracy	expressive-latency
hyper-IDS	-.05	.02	.14	-.09
non-hyper-IDS	-.24	-.38	.32	-.08
hyper-ADS	.47*	-.65*	.29	-.61^

**p* = .01; ^*p* = .06

5.4 Discussion

This study assessed the effects of the vowel hyperarticulation component on 18-month-old infants' lexical processing performance by manipulating its presence in both IDS and ADS. The results supported our prediction that exaggerated prosody aids lexical processing showing that infants achieved greater accuracy and shorter latencies in *hyper*-IDS and *non-hyper*-IDS compared to the *hyper*-ADS condition. Importantly, infants did not show word recognition and produced the longest response latencies in the *hyper*-ADS condition. The findings from correlational analyses demonstrating that infants with smaller vocabularies were slower in recognising the words lacking the vowel hyperarticulation suggest that vowel hyperarticulation as a clarity cue in IDS facilitates infants' performance on a lexical processing task for both infants with smaller and larger vocabularies but only when it occurs in combination with the prosodic cues of IDS.

Our findings indicate that exaggerated prosody in IDS supports lexical processing even when the vowel hyperarticulation component is absent. This is consistent with previous studies showing that prosodic exaggeration in IDS facilitates infants' performance on word segmentation, word recognition, and word-learning tasks (Ma et al., 2011; Singh et al., 2009;

Thiessen et al., 2005). Also, this is in accordance with Song et al. (2010) who showed that infants' lexical processing accuracy did not differ when listening to IDS when its exaggerated prosody remained intact, regardless of whether vowel hyperarticulation was present or absent. These findings suggest that vowel hyperarticulation is not sufficient to facilitate lexical processing independently from other IDS features.

However, our correlational analyses suggest that infants' reliance on the prosodic and speech clarity cues in IDS and ADS were modulated by their individual vocabulary knowledge. In the *hyper*-ADS condition, infants with larger receptive vocabularies achieved greater accuracy and shorter response latencies. A similar trend was observed in the *non-hyper*-IDS condition. In the *hyper*-IDS condition, there were no significant correlations between vocabulary sizes and accuracy and latency measures. These findings suggest that when infants with smaller vocabulary sizes were faced with challenging speech conditions such as an unfamiliar speech register that does not contain prosodic exaggeration (i.e., ADS) or IDS that lacks vowel hyperarticulation, they showed poorer lexical processing performance. On the contrary, infants achieved successful word recognition when presented with *IDS with vowel hyperarticulation* regardless of their vocabulary size. These findings dovetail with Ma et al. (2011) who showed that as a group, 21-month-old infants were more successful in learning novel words presented in IDS compared to ADS. However, at the individual level, infants with larger expressive vocabularies succeeded in the ADS condition suggesting that greater lexical competence reduces infants' dependence on the acoustic exaggeration in IDS. It is therefore possible that infants' response accuracy and latency in the ADS condition would approximate the IDS conditions in our study if tested several months later (e.g., 27-month-olds in Ma et al., 2011 were successful at learning novel words presented in ADS). Similarly, a *hyper*-IDS vs. *non-hyper*-IDS effect may emerge among younger infants who have smaller lexical competence and whose lexical representations are still being specified, and thus who would benefit more from acoustic representations in their familiar speech register (Zangl & Mills, 2007).

To isolate the effects of vowel hyperarticulation on lexical processing, we constructed two conditions where this feature was present, IDS and ADS. However, it is possible that vowel hyperarticulation in our stimuli was not identical to this component occurring in natural IDS and ADS, where it can originate from different sources (Tang et al., 2017). Previous studies have showed that speakers' production of hyperarticulated vowels may differ depending on the audience. Kalashnikova and colleagues (2017) found that vowel hyperarticulation in IDS is the product of vocal tract shortening resulting from laryngeal raising. This results in higher pitch and increased formant values, allowing the speaker to appear smaller and less threatening to their audience (Ohala, 1980, 1984). Thereby, mothers produce speech that is more comforting to infants, attracts their attention to speech, and serves a secondary linguistic function of producing vowels that are easier for infants to perceive, discriminate, and later reproduce in their own vocal tract (Kalashnikova et al., 2017). On the other hand, vowel hyperarticulation in ADS is a product of shortening of the front cavity and widening of the pharyngeal tract by joint movements of the jaw (increasing the loudness) and the tongue (enhancing the vowel quality) (Erickson, 2002; Harrington, Fletcher, & Beckman, 2000). Although vowel hyperarticulation in both IDS and ADS results in clearer, more intelligible speech, it could be that these differences in the patterns of vowel production influenced infants' vowel perception and consequently their performance on our lexical processing task.

It is also possible that infants' lack of interest in the ADS condition overall limited our ability to detect their reliance on the vowel hyperarticulation component in the *hyper*-ADS condition. It is known that IDS is more effective in attracting infants' attention than ADS (Cooper & Aslin, 1990; Fernald & Simon, 1984). Our track loss analysis provides further evidence for this, since from the 721 excluded trials, only 126 were from the *hyper*-IDS and

171 were from the *non-hyper*-IDS conditions, whereas 424 trials were from the *hyper*-ADS condition. It is possible that reduced attention to the task resulting in the greatest loss of data in *hyper*-ADS condition influenced infants' response accuracy and latency.

Unlike our findings with infants, it has been demonstrated that vowel hyperarticulation facilitates lexical processing in adults (van der Feest et al., 2019). While van der Feest and colleagues (2019) have found that vowel hyperarticulation in the context of clear speech aids adults' lexical processing, our *hyper*-ADS condition did not show this facilitative effect of vowel hyperarticulation. This does not necessarily mean that vowel hyperarticulation does not have facilitative effects on infants' lexical processing. It could be that vowel hyperarticulation only in natural IDS is beneficial for infants while for adults, vowel hyperarticulation is beneficial when it is present in clear speech, a register familiar to them. In other words, it could be that listeners experience the greatest benefit during language processing tasks from the speech register most familiar to them. Therefore, it is possible that the privileged status of IDS in facilitating infants' performance in a language processing task is dependent on the combination not only of the acoustic features assessed here, but also its other visual (Chong et al., 2003), lexical, and grammatical features (Soderstrom et al., 2008).

5.4.1 Conclusion.

Previous research has described the distinctive features of IDS and has provided evidence that IDS facilitates infants' performance on different language tasks and may foster infants' language development. However, it is important to clarify the role of these distinctive IDS features in supporting different language skills. To assess the effect of vowel hyperarticulation as the speech clarity cue in IDS on infants' lexical processing, three different manipulations were implemented in this study. The results support an important role of exaggerated prosody in IDS in facilitating infants' lexical processing and suggest that typical

IDS, with combined attentional and clarity cues, provides a rich input that facilitates infants' lexical processing and language acquisition.

However, this experiment assessed the roles of IDS features in lexical processing at 18 months of age, when infants are already experienced word learners reaching the 50-word mark in expressive vocabulary (Robb et al., 1994). It could be that vowel hyperarticulation and pitch have different effects on lexical processing in very young infants. Thus, in order to obtain a complete picture of the roles of specific IDS features in lexical processing, it is important to assess their effect in young infants with small lexicons. Therefore, in the next Chapter, we will turn our attention to the effects of IDS prosody and vowel hyperarticulation on infants' lexical processing during the early stages of lexical acquisition. As in this experiment, this was achieved by manipulating the presence of vowel hyperarticulation and pitch in IDS and ADS and assessing the effects of these features on the neural processing of speech in six- and 10-month-old infants.

CHAPTER 6

The Role of the Acoustic Features of IDS on Early Lexical Processing at the Neural Level

6.1 Introduction

Chapter 5 assessed the effects of the vowel hyperarticulation component on 18-month-old infants' lexical processing performance by manipulating its presence in both IDS and ADS. The results demonstrated that infants achieved greater accuracy and shorter response latencies in *hyper*-IDS and *non-hyper*-IDS compared to the *hyper*-ADS condition. Importantly, infants did not show word recognition and produced the longest response latencies in the *hyper*-ADS condition. These findings suggest that vowel hyperarticulation only facilitates lexical processing in infants when it occurs in combination with the prosodic cues of IDS. However, this experiment was conducted with 18-month-old infants who are already experienced word learners, so it is possible that vowel hyperarticulation does play a unique role in lexical processing in much younger infants whose lexicons are in their very earliest stages. In order to obtain a complete picture about how specific features of IDS such as vowel hyperarticulation and exaggerated pitch height can influence lexical processing, it is important to examine these features during the early stages of lexical processing. This can be achieved by using electrophysiological methods (electroencephalography (EEG) /event-related potentials (ERPs)), which can provide step-wise temporal processing of these features. Thus, the goal of this Chapter is to assess whether there is a difference in lexical processing of exaggerated pitch height and vowel hyperarticulation components of IDS at the neural level in six- and 10-month-old infants.

6.1.1 Neural indices of word recognition.

Event-related potentials (ERPs) are averages of electrical activity from multiple neurons in the brain time-locked to specific stimuli (Coles & Rugg, 1995; Handy, 2005; Kutas & Dale, 1997). Recorded using electrodes placed on the scalp, ERPs reflect rapid changes in brain activity over time and are usually recorded with a temporal resolution on the millisecond scale from multiple scalp locations. They are characterised by a series of positive and negative peaks in voltage known as components. The amplitude of the ERP components reflects differences in event-related neural activity by reflecting the strength of the neuronal output in response to an event, where multiple neurons fire simultaneously to produce activity, whereas the component latencies can reflect information about the timing of neural events (Coles & Rugg, 1995). The polarity (positive/negative) of the neural response recorded at the scalp, latency and scalp distribution of different components allow us to dissociate particular cognitive processes associated with them. In particular instances, these could be interpreted as the slowing down of a specific cognitive process (usually reflected in ERP latency), a reduction in the processing demands or efficiency (usually reflected in ERP amplitude) of a positivity or negativity, or a change in the potential cortical distribution underlying a particular cognitive process (topography). Some of the benefits of the ERP technique in infant research consist in this technique not requiring an overt response, as well as being safe and non-invasive.

In this experiment, infants were stimulated auditorily by presentations of isolated words. ERPs were investigated in two time-windows: between 250-500ms and between 600-900ms after word onset. The first time-window enabled us to assess the N250-500 component, which is a negative waveform that peaks at around 250ms after stimulus onset. It has been found to correlate with phonological and lexical processing in infants (Kooijman et al., 2005; Mills et al., 1993; Thierry, Vihman, & Roberts, 2003; Zangl & Mills, 2007). Kooijman and colleagues (2005) conducted an ERP study on word segmentation in 10-month-old infants acquiring Dutch. In this study, they familiarised infants to isolated words and then tested them on passages containing either familiarised or novel words. In both the familiarisation and testing phases, they found more negative ERP responses that appeared 200 to 500ms after word onset. Similar ERP responses have also been found in word recognition studies in 11- and 20-month-old infants for both familiar words and pseudo-words (Mills et al., 1993; Thierry et al., 2003; von Koss Torkildsen et al., 2009). Authors interpreted this effect as an effect of word-form familiarity through repetition indicating recognition of familiar words in 10-month-olds. Thus, the N250-500 component can be interpreted as an ERP indicator of word recognition.

The second component of interest here is the Nc component, a negative component peaking around 800ms after stimulus onset (Courchesne, 1977). It has been suggested that an increased Nc reflects increased allocation of attention to a stimulus (Nelson & Monk, 2001). The results of previous studies suggest that the Nc component is a stimulus-driven automatic attentional response that reflects automatic orienting to stimulus change (Vaughan & Kurtzberg, 1992) or selective attention to important, surprising or interesting stimuli (Courchesne, 1977). Reynolds and Richards (2005) demonstrated a larger negative Nc component in four-, five-, six-, and seven-month-old infants for novel compared to familiarised stimuli indicating greater attention to the novel stimuli. Additionally, in infant studies, larger Nc responses have been found to be typically elicited by highly familiar stimuli such as infants' mothers' faces compared to unfamiliar faces, to favourite toys compared to other toys, and to a familiar speech register - IDS (Ackles & Cook, 2009; de Haan & Nelson, 1997, 1999; Richards, 2003; Zangl & Mills, 2007), confirming its interpretation as an ERP indicator of attention-related processes.

6.1.2 Neural processing of IDS and ADS in young infants.

In recent years, there has been an increasing interest in using electrophysiological methods to investigate different language processing skills in infants. Previous studies demonstrated increased brain activity to IDS compared to ADS (Saito et al., 2007; Santesso et al., 2007; Zhang et al., 2011). To date, there has been only one study that investigated *lexical processing* in IDS and ADS at the neural level (Zangl & Mills, 2007). Zangl and Mills (2007) recorded ERPs from six- and 13-month-old infants while they listened to familiar or unfamiliar words in either IDS or ADS. Their results demonstrated a larger Nc response to IDS for familiar words than ADS over the left hemisphere between 600-800ms from word onset in six-month-old infants suggesting increased attention allocated to words presented in IDS. In contrast, 13-month-old infants produced a larger response between 200-400ms (this was suggested to be an N400 – an indicator of semantic processing) for familiar words presented in IDS, suggesting an increased ability to understand familiar words presented in IDS as compared to ADS. Additionally, they found a larger bilateral Nc response between 600-800ms for both familiar and unfamiliar words in IDS compared to ADS. This effect was attributed to increased attention to and arousal by IDS stimuli compared to ADS stimuli. These findings are consistent with findings from behavioural studies suggesting a facilitative effect of IDS prosody, specifically exaggerated pitch height and pitch range in infants' word segmentation (Thiessen et al., 2005), discrimination of speech sounds (Trainor & Desjardins, 2002), and novel word-referent mapping (Graf Estes & Hurley, 2013; Ma et al., 2011). However, given the finding that prosodic exaggeration in IDS does not appear to be related to infants' developing linguistic skills (Suttora et al., 2017), it is not clear whether IDS prosody only serves an attentional role in IDS, or whether it has a linguistic role as well and thus has an effect on lexical processing.

The increased brain activity to IDS over ADS demonstrated in previous studies may be due to attentional features of IDS (Saito et al., 2007; Santesso et al., 2007; Zangl & Mills, 2007; Zhang et al., 2011). However, given that infants' preference for specific IDS features changes with increasing age and language experience (Cristia, 2013; Hayashi et al., 2001; Newman & Hussain, 2006; Saint-Georges et al., 2013; Segal & Newman, 2015), it is possible that different features play an attentional role in IDS. Indeed, it has been shown that parents adjust their IDS features according to infants' age resulting in IDS features that are pronounced during the first months of life, only to become less salient with increasing infant age (Kitamura & Burnham, 2003; Stern et al., 1983). In order to investigate the age-dependent roles of IDS features, Männel and Friederici (2010, 2013) assessed the role of prosodic adjustments and repetition in six-, nine-, and 12-month-old infants' word segmentation using ERPs. Their results showed that at six months, prosodic features of IDS drive word segmentation, that both prosodic adjustments and word repetition are important cues at nine months, but only word repetition drives word segmentation at 12 months.

Two studies have investigated neural processing of particular IDS features. Zhang and colleagues (2011) investigated six- to 12-month-old infants' neural responses to vowels, which were formant-exaggerated in order to simulate vowel hyperarticulation in IDS. They found larger P150 and N250 responses to formant-exaggerated vowels compared to non-exaggerated vowels. The P150 component was suggested to reflect the acoustic mapping of spectral differences between the stimuli (Rivera-Gaxiola et al., 2007), while the N250 component is a measure of phonological and lexical processing in infants (Mills et al., 2004; Rivera-Gaxiola et al., 2007; Zangl & Mills, 2007). These findings suggest that formant expansion in IDS enhances discrimination of vowels. The second study of neural processing of particular IDS features was conducted in nine-month-old infants (Peter et al., 2016). In this study, infants heard two instances of the vowel /i/, one extracted from IDS and one from ADS in two oddball conditions ADS standard/IDS deviant and IDS standard/ADS deviant. The presence of a mature adult-like mismatch negativity (MMN) for the vowel /i/ presented in IDS indicated that the IDS stimulus was easier to discriminate for infants. These electrophysiological findings are in accordance with behavioural evidence demonstrating a facilitative effect of vowel hyperarticulation in IDS in spoken language processing in 19-month-olds (Song et al., 2010).

6.1.3 Chapter aims and research questions.

Although previous studies suggest a linguistic role of vowel hyperarticulation of IDS in infants' language acquisition, recent evidence as well as the findings reported in Chapters 3 and 4 contradict this by showing a lack of vowel hyperarticulation in some languages and the presence of greater variability in vowel production in IDS compared to ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). The experiment reported in this Chapter manipulated the presence and absence of pitch height and vowel hyperarticulation in IDS and ADS to assess six- and 10-month-old infants' neural responses to these features. These ages were selected given that they mark important developmental milestones in language acquisition. At around six months of age, infants become attuned to vowel categories in their native language (Polka & Bohn, 1996; Polka & Werker, 1994). Furthermore, between nine to 12 months, infants develop native speech perception abilities: the sensitivity to native-language contrasts increases, while it decreases for non-native contrasts (Werker, 2003; Werker, Yeung, & Yoshida, 2012). Additionally, this age is interesting since this is when infants' preference for IDS over ADS decreases (Hayashi et al., 2001; Newman & Hussain, 2006). With regard to infants' lexicon at these ages, between six and nine months of age infants are able to recognise their own name, sound patterns associated to significant persons in their life (e.g. "mommy", "daddy") as well as words related to food and body parts (Bergelson & Swingley, 2012, 2015; Tincoff & Jusczyk, 2012). Additionally, at 10 months of age, infants' word recognition is not mainly associative but referential in nature, showing that infants do understand the meanings of words (Parise & Csibra, 2012).

Three within-subjects conditions were used in this experiment following the rationale presented in Chapter 5: *hyper-IDS*, *non-hyper-IDS*, and *hyper*-ADS, manipulating the presence of exaggerated pitch height and hyperarticulated vowels. In the *hyper*-IDS condition, speech consisted of acoustic exaggerations typical of natural IDS such as exaggerated pitch height and hyperarticulated vowels. The *non-hyper*-IDS condition consisted of exaggerated pitch height typical of natural IDS, but with no vowel hyperarticulation. The *hyper*-ADS condition employed only one acoustic exaggeration from IDS - vowel hyperarticulation - while the pitch height was typical of ADS (lower pitch height compared to IDS). In order to assess infants' lexical processing skill, each condition (*hyper*-IDS, *non-hyper*-IDS, and *hyper*-ADS) included words that are familiar and words that are unfamiliar to young infants. The research questions and hypotheses were as follows:

1. *Do ERP responses to pitch height and vowel hyperarticulation differ as a function of a word's familiarity?* In order to answer this question, each condition (*hyper*-IDS, *non-hyper*-IDS, and *hyper*-ADS) included words that are familiar and words that are unfamiliar to infants. Given the evidence related to the attentional role of pitch height in IDS, we expect increased Nc amplitudes for familiar words in registers with exaggerated pitch height (*hyper*-IDS, *non-hyper*-IDS) in the 600-900ms time-window. On the other hand, if vowel hyperarticulation mainly has a linguistic function, thus, to facilitate infants' processing of the words (Song et al., 2010), we expect larger amplitudes for unfamiliar words in registers with hyperarticulated vowels (*hyper*-IDS, *hyper*-ADS) in the early time-window (250-500ms).
2. *Does pitch height or vowel hyperarticulation affect infants' attention and lexical processing at the neural level?* First, if the pitch height feature of IDS drives attention to speech, we expect greater amplitudes in the 600-900ms time-window in the two conditions with exaggerated pitch height (*hyper*-IDS, *non-hyper*-IDS) compared to the condition with lower pitch height (*hyper*-ADS) (Graf Estes & Hurley, 2013; Thiessen et al., 2005). Second, if vowel hyperarticulation facilitates lexical processing, larger N250-500 amplitudes would be expected in the conditions with higher degree of vowel hyperarticulation (*hyper*-IDS, *hyper*-ADS) compared to the condition without vowel hyperarticulation (*non-hyper*-IDS) (Song et al., 2010).

3. *Do ERPs to pitch height and vowel hyperarticulation differ as a function of infants' age?* Given the findings that pitch-height preferences differ across infants' ages with greater pitch-height preferences at four to six and at 12-months of age and lower pitch-height preferences at nine-months (Kitamura & Burnham, 2003; Kitamura et al., 2001; Stern et al., 1983), it was expected that neural responses to speech registers differing in pitch height will follow this pattern. Thus, at six months, greater amplitudes in the 600-900ms time-window were expected for the two conditions with exaggerated pitch height (*hyper*-IDS, *non-hyper*-IDS) compared to the *hyper*-ADS condition. At 10 months, greater amplitudes in the 600-900ms time-window were expected for the condition with the lowest pitch height (*hyper*-ADS) compared to *hyper*- and *non-hyper*-IDS conditions. However, if vowel hyperarticulation drove infants' lexical processing, it was expected that this would be reflected in developmental patterns as well. While previous studies demonstrated that the prevalence of vowel hyperarticulation is stable across development (D. Burnham et al., 2002; E. Burnham et al., 2015; Cristia & Seidl, 2014; Kalashnikova & Burnham, 2018), it has been found that the degree of vowel hyperarticulation in maternal speech to nine-month-olds, but not younger infants, is related to infants' vocabulary development at 19 months, suggesting that vowel hyperarticulation is more important in older compared to the younger infants (Kalashnikova & Burnham, 2018). Therefore, it is expected that vowel hyperarticulation would have a greater facilitative effect in lexical processing for 10-month-old compared to six-month-old infants. Consequently, at six months, greater amplitudes in the 250-500ms time-window were expected for the condition with the lowest degree of vowel hyperarticulation (*non-hyper*-IDS) compared to both *hyper*-IDS and *hyper*-ADS conditions. In contrast, at 10 months, greater amplitudes in the 250-500ms time-window were expected for the two conditions with greater degree of vowel

hyperarticulation (*hyper-IDS*, *hyper*-ADS) compared to the *non-hyper*-IDS condition (Bernstein Ratner, 1984; Burkinshaw, Holt, & Curtin, 2019).

6.2 Method

6.2.1 Participants.

Twenty-three six-month-old and 26 10-month-old infants participated in this experiment. Due to an unsatisfactory number of artefact-free trials, excessively noisy data, equipment failure and task non-completion, 10 infants from the six-month-old group and 10 from the 10-month-old group were excluded. Thus, the final sample consisted of 13 six-month-old infants (7 females; *Mean age* = 6.01, *SD* = .62, *Age range* = 5.06 – 7.63) and 16 10-month-old infants (7 females; *Mean age* = 9.76m, *SD* = .77, *Age range* = 8.71 – 10.98). All infants were raised in Australian English monolingual families. They were born full-term with NH, and none were found to be at-risk for any developmental disorders.

6.2.2 Stimuli.

Thirty words familiar and 30 words unfamiliar to infants were used. Words were chosen based on Zangl and Mills (2007) and their familiarity to infants was confirmed by using the Wordbank database (Frank, Braginsky, Yurovsky, & Marchman, 2016). Since this database for Australian English only provides vocabulary trajectories related to word production and only for infants over 12 months of age, the receptive vocabulary trajectory for American English was used. Growth curves for individual words were explored and words that between 25% and 50% of infants between six and 10 months of age can understand were chosen as familiar. Additionally, before each testing session, parents were asked to complete a vocabulary checklist that contained all word stimuli used in the study and to choose the ones familiar to their infant. This was done to ensure that words used in the study were familiar to the infants. It was decided that if over 50% of words that represent familiar words in the experiment were unfamiliar to an infant, that infant should be excluded from the experiment. Higher level of unfamiliar words was found in infants who were already excluded because of failure to complete the task.

A female native speaker of Australian English was recorded producing the stimuli. The speaker produced all stimuli without addressing an interlocutor, but she followed specific instructions for each experimental condition. She was instructed to produce the words pretending that she was talking to an infant (20 words, *hyper*-IDS), to an adult (20 words, *hyper*-ADS) and to pretend that she was talking to an infant preserving the pitch but shortening the vowels (*non-hyper*-IDS). Also, she was instructed to repeat the words three to five times, so in total 200 different instances of stimuli were recorded. All recorded instances were analysed using Praat (Boersma & Weenink, 1996) for the following parameters: word duration, average fundamental frequency (F0), and first and second formant frequencies (F1 and F2). Using the F1 and F2 values, vowel space area was calculated for corner vowels /a, i, u/ in a same way as was done in Chapters 3 and 4 using the method proposed by Kuhl et al. (1997). Instances with the highest values for those parameters were chosen for the *hyper*-IDS stimuli, while those with the lowest values and lower values were chosen for the *hyper*-ADS and *non-hyper*-IDS stimuli, respectively. With regard to pitch height, a univariate ANOVA confirmed a significant difference across conditions ($F(2, 57) = 21.42$, $p < .001$, $\eta_p^2 = .43$). Post-hoc Bonferroni comparisons demonstrated greater pitch height in both *hyper*-IDS ($M = 280.54$ Hz, $SD = 40.48$) and *non-hyper*-IDS ($M = 268.42$ Hz, $SD = 57.36$) conditions compared to the *hyper*-ADS condition ($M = 191.01$ Hz, $SD = 40.97$), $p < .001$. Pitch height did not differ significantly between *hyper*-IDS and *hypo*-IDS conditions, $p = 1.00$. In order to ensure that the degree of vowel space area was greater in the *hyper*-articulation conditions (*hyper*-IDS, *hyper*-ADS) compared to the *non-hyper*-IDS condition, vowel space areas were calculated for each condition. A one-way ANOVA showed that there was a significant difference in vowel space area across conditions ($F(2, 59) = 8.40$, $p < .001$, $\eta_p^2 = .43$). The degree of vowel space area was the greatest in *hyper*-IDS (M = 378094.792 Hz^2) compared to both *hyper*-ADS (M = 239579.325 Hz^2) and *non-hyper*-IDS (M = 208395.71 Hz^2). Additionally, a univariate ANOVA confirmed a significant difference in word duration across conditions ($F(2, 57) = 16.32$, $p < .001$, $\eta_p^2 = .36$). Post-hoc Bonferroni comparisons demonstrated longer word duration in *hyper*-IDS (M = .71 ms, SD = .14) compared to both *non-hyper*-IDS (M = .54 ms, SD = .14) and *hyper*-ADS conditions (M = .49 ms, SD = .08), $p < .001$. The words chosen for each condition are shown in the Appendix D. In order to ensure that all words had the same intensity level, they were normalised using Audacity 2.2.1 and converted to stereo using Praat (Boersma & Weenink, 1996).

6.2.3 Design.

The procedure consisted of 60 different words being presented in six different conditions: 10 familiar words in *hyper*-IDS, 10 familiar words in *non-hyper*-IDS, 10 familiar words in *hyper*-ADS, 10 unfamiliar words in *hyper*-IDS, 10 unfamiliar words in *non-hyper*-IDS, and 10 unfamiliar words in *hyper*-ADS. Each word was repeated five times randomly for a total of 50 trials per condition (300 trials in total). To minimise data loss, the stimuli were divided into four blocks with 150 words in each block since having four blocks allowed having breaks between blocks in cases when infants became fussy during the testing. Presentation 16.3 (Neurobehavioral Systems) software was used for stimulus presentation.

6.2.4 EEG recording.

The infants sat on their parent's lap approximately 1m from an LCD screen and watched an age-appropriate silent cartoon chosen by the parent. Continuous EEG was recorded using a 129-channel Hydrocel Geodesic Sensor Net (HCGSN), NetAmps 300 amplifier and NetStation 4.5.7 software (EGI Inc) at a sampling rate of 1000 Hz. Data were referenced online to Cz.

6.2.5 Challenges of EEG testing in infancy.

Although the EEG technique is a safe and non-invasive method for investigating neurophysiological processes, there are some challenges in using this method with infants. These challenges are mostly related to data collection and consist of infants' cooperation with the placement of the electrodes as well as the stability of the electrodes on the head over the duration of the experiment (de Haan, 2007). Furthermore, it can be quite challenging to minimise movements during the task, resulting in a higher degree of artefacts compared to EEG data collection in adults (de Haan, 2007). These issues lead to high number of participants whose data need to be removed with retention rates of participants being age dependent (e.g. 62% at four to seven months, 65% at nine months, 50% at 12 months (Courchesne, Ganz, & Norcia, 1981; DeBoer, Scott, & Nelson, 2007; Zangl & Mills, 2007). Apart from challenges concerning data collection, other challenges include those related to data analysis and interpretation. In interpreting infants' ERP data, attention should be paid to developmental changes in EEG rhythms and ERP components, due to brain maturational processes, changes in synaptic density and changes in myelination (DeBoer et al., 2007; Luciana & Nelson, 1998). Changes in synaptic density lead to developmental changes in amplitude (Vaughan & Kurtzberg, 1992), while changes in brain myelination lead to developmental changes in latency (Ponton, Moore, & Eggermont, 1999) of the responses. Furthermore, individual differences in these brain maturational mechanisms may lead to differences in amplitude and latency which will not necessarily show up in grand averages of ERP data (Kidd, Junge, Spokes, Morrison, & Cutler, 2018). In addition, within-participant variability in infant ERP data may stem from changes in infant states during data collection (e.g., sleepiness, fussiness) (DeBoer et al., 2007). However, these challenges in ERP testing in infancy researcher can overcome in different ways. In this experiment, the first step taken to overcome these challenges included using the Geodesic Sensor Net (GSN) that allows large numbers of electrodes (from 64 to 256) to be placed quickly on the infant's head (Tucker, 1993). Additional steps that we undertook in this experiment consisted of designing the experiment with faster testing times, smaller stimuli blocks, pauses between blocks and calming infant with toys, animated movies or bubbles.

6.2.5 Offline analysis.

The EEG data were analysed offline using EEGLAB v14.1.1 (Delorme & Makeig, 2004) in MATLAB2014b (MathWorks, Natick, 2014). First, the data were re-referenced to the average of left and right mastoid. Next, in order to increase the signal to noise ratio (SNR) and attenuate unwanted frequencies from the data, the continuous EEG was band-pass-filtered using a Basic FIR filter between 0.3-20 Hz. Then, visual inspection of the data was conducted to detect noisy EEG channels that were then interpolated by averaging the neighbouring electrodes weighted by distance (average: 4 channels/subject, range 0-10). Next, further cleaning of the continuous EEG data was conducted using Artifact Subspace Reconstruction (ASR, Mullen et al., 2013). Data were divided into epochs from -100 to 1100ms relative to sound onset. The pre-stimulus 100ms time-window was used for baseline correction. The epochs were averaged separately for each condition to obtain six ERP waveforms per participant (*hyper*-IDS familiar, *hype*r-IDS unfamiliar, *non-hyper*-IDS familiar, *non-hyper*-IDS unfamiliar, *hyper*-ADS familiar, *hyper*-ADS unfamiliar). The waveforms from individual participants were averaged to create grand-average waveforms.

6.2.6 Measures.

For electrophysiological measures, mean amplitudes were calculated for selected time-windows as follows:

- 250-500ms interval, as a measure of lexical processing (N250-500);
- 600-900ms interval, as a measure of sustained attention to the familiar words (Nc).

6.3 Results

Since previous ERPs studies demonstrated that ERP components change as a function of infant age (Eggermont & Moore, 2012; Männel & Friederici, 2013), data were analysed separately for 6- and 10-month-old infants. The data for each age group and each ERP component were analysed in separate repeated-measures analyses of variance (ANOVAs) using SPSS 22. Greenhouse-Geisser corrections were used where applicable. Within-subjects factors consisted of three levels of Speech Register (*hyper*-IDS, *hypo*-IDS, ADS), two levels of Word Familiarity (familiar, unfamiliar), two levels of Hemisphere Specialisation (left, right), and four levels of Electrode Site along the anterior-posterior axis (frontal, central, parietal, occipital, see Figure 20). In order to make results easier to parse, in this section, only results relevant to the a-priori specified research questions and predictions are presented here and the full output of the models can be found in the Appendix E.

6.3.1 The roles of pitch and vowel hyperarticulation in lexical processing in 6-month-old infants.

In order to assess the role of pitch and vowel hyperarticulation in lexical processing and attentional preference respectively in 6-month-old infants, 3 Speech Register (*hyper*-IDS, *non-hyper*-IDS, *hyper*-ADS) x 2 Familiarity (familiar, unfamiliar) x 4 anterior-posterior Electrode Site (Frontal, Central, Parietal, Occipital) x 2 Hemispheric Specialisation (left, right) repeated-measures ANOVAs were conducted for amplitudes in 250-500ms and 600-900ms time-windows.

With regard to the roles of pitch and vowel hyperarticulation in 6-month-old infants' lexical processing, the repeated-measures ANOVA did not demonstrate any significant effects or interactions in the 250-500ms time-window (see the Appendix E for further details). Also, there were no significant main effects or interactions in 600-900ms time-window that assessed the roles of pitch and vowel hyperarticulation in attentional preference for IDS in 6-month-old infants (see the Appendix E for further details).

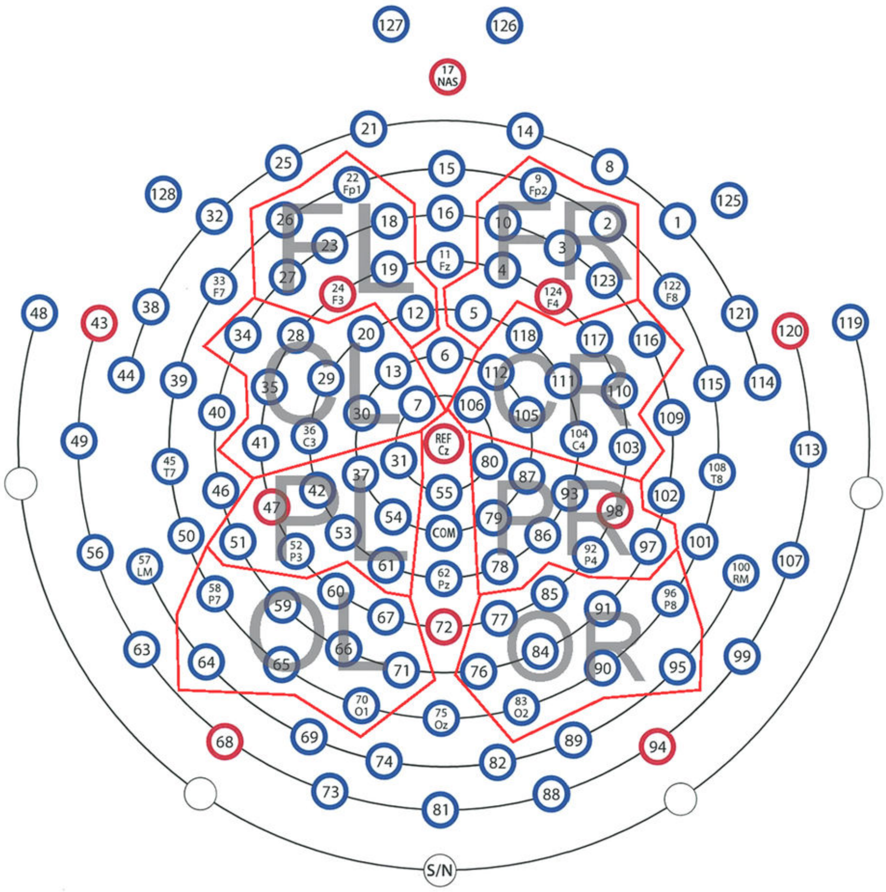

Figure 20. Electrode regions of interest used for analyses (frontal left (FL), frontal right (FR), central left (CL), central right (CR), parietal left (PL), parietal right (PR), occipital left (OL), occipital right (OR)) (Figure from Peter, V., Kalashnikova, M., Santos, A., & Burnham, D. (2016). Mature neural responses to infant-directed speech but not adult-directed speech in pre-verbal infants. *Scientific reports*, *6*, 34273.).

6.3.2.1 250-500ms time-window.

The results for this time-window demonstrated a significant Speech Register by Familiarity interaction ($F(2, 30) = 7.40$, $p = .01$, $\eta_p^2 = .33$). Bonferroni post hoc analyses revealed that in the *non-hyper*-IDS condition, familiar words elicited more negativity (i.e., larger mean amplitude; M = -1.01, SD = 1.91) than unfamiliar words (M = .11, SD = 2.02), ($F(1, 15) = 7.00$, $p = .02$, $\eta_p^2 = .32$) (see Figure 21 for ERP waveforms). On the other hand, in the *hyper*-ADS condition, unfamiliar words elicited more negativity (M = -1.25, SD = 1.94) than familiar words (M = .43, SD = 1.24), ($F(1, 15) = 10.76$, $p = .01$, $\eta_p^2 = .42$). No familiarity effect was found for words in the *hyper*-IDS condition ($F(1, 15) = 2.76$, $p = .12$, $\eta_p^2 = .16$).

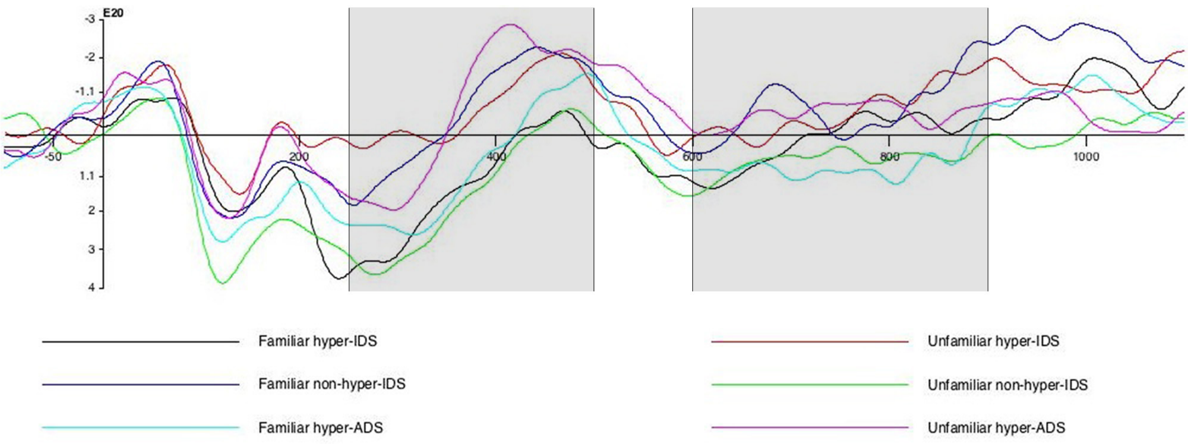

Figure 21. ERP waveforms for 10-month-old infants to familiar words in *hyper*-IDS (black line), unfamiliar words in *hyper*-IDS (red line), familiar words in *non-hyper*-IDS (dark blue line), familiar words in *non-hyper*-IDS (green line), familiar words in *hyper*-ADS (blue line), and unfamiliar words in *hyper*-ADS (purple line); Grey boxes represent 250-500ms and 600-900ms time-windows respectively.

6.3.2.2 600-900ms time-window.

A Speech Register by Familiarity interaction was significant ($F(2, 30) = 4.86$, $p = .02$, $\eta_p^2 = .24$). Bonferroni post-hoc test showed that in the *non-hyper*-IDS condition, familiar words elicited more negativity (i.e., M = -.71, SD = 1.69) than unfamiliar words (M = .54, SD = 1.8), ($F(1, 15) = 7.73$, $p = .01$, $\eta_p^2 = .34$). In the *hyper*-ADS condition, unfamiliar words elicited more negativity (M = -.01, SD = 1.57) compared to familiar words (M = 1.10, SD = .95) (F(1,

15) = 5.94, p = .03, η_p^2 = .28). There was no significant effect of familiarity on words in the *hyper*-IDS condition (F(1, 15) = .20, p = .66, η_p^2 = .01) (see Figure 21 for ERP waveforms).

6.4 Discussion

This study assessed the neurophysiological response to pitch height and vowel hyperarticulation in six- and 10-month-old infants by manipulating the presence of these features in both IDS and ADS. In the first - *hyper*-IDS - condition, stimuli were presented in speech with exaggerated pitch height and hyperarticulated vowels, which are features of natural IDS. In the second condition - *non-hyper*-IDS - stimuli were presented in speech that retained the exaggerated pitch height of natural IDS, but that lacked the vowel hyperarticulation component. The third condition - *hyper*-ADS - consisted of speech with lower pitch height typical for natural ADS, but with hyperarticulated vowels, similar to typical IDS. Three main questions were raised regarding linguistic and attentional roles of these components. In the following paragraphs the findings will be discussed in light of these questions.

In this experiment we were interested in ERP differences to pitch height and vowel hyperarticulation as a function of age and word familiarity respectively. Given the evidence suggesting adjustments in maternal IDS over development as a result of infants' age and linguistic needs, it was predicted that neural responses to these two IDS components would follow this developmental pattern. While our results were not in line with these predictions in six-month-old infants, the IDS components showed varying effects in 10-month-old infants. The results demonstrated that in 10-month-olds, the ERP negativity in the early time-window (250-500ms) was larger in amplitude for the *hyper*-ADS condition for unfamiliar words followed by familiar words in the *non-hyper*-IDS, unfamiliar words in the *non-hyper*-IDS and familiar words in the *hyper*-ADS conditions. Given that ERP effects in this time-window have been suggested to be a measure of word repetition or word recognition effects (Kooijman et al., 2005; Mills et al., 1993; Thierry et al., 2003; Zangl & Mills, 2007), greater negativity here lends support to the linguistic role of vowel hyperarticulation. Thus, when infants listened to words that were not familiar to them, they exhibited the greatest word repetition effect when these words were spoken with hyperarticulated vowels and low pitch height. This is in line with findings from behavioural studies that demonstrated a relationship between the vowel hyperarticulation component in IDS spoken to nine-month-old infants and infants' subsequent expressive vocabulary development at 19 months (Kalashnikova & Burnham, 2018). On the other hand, the results in the present experiment showed that when infants listened to the words in the *non-hyper*-IDS register (with exaggerated pitch height and a lower degree of vowel hyperarticulation) larger amplitudes were found for familiar versus unfamiliar words. These findings indicate that when infants are exposed to words unfamiliar to them, the vowel hyperarticulation feature may drive their acquisition of these words. On the other hand, if infants are exposed to words that are highly familiar to them, the exaggerated pitch height of IDS drives infants' recognition of these words. With regard to the *hyper-IDS* condition (speech with exaggerated pitch height and vowel hyperarticulation), we did not observe any significant effects at this age (10 months). This could be due to the greatest degree of pitch height in this condition failing to make this speech register attractive to infants. Indeed, previous studies have demonstrated that infants at this age are usually exposed to IDS with lower pitch height (Kitamura & Burnham, 2003; Kitamura et al., 2001; Stern et al., 1983).

For the word processing during the later time-window (600-900ms), the results revealed significant differences in neural responses to *non-hyper*-IDS and *hyper*-ADS. Negative amplitudes (Nc) were largest for familiar words in the *non-hyper*-IDS condition followed by unfamiliar words in *hyper*-ADS, unfamiliar words in *non-hyper*-IDS, and familiar words in *hyper*-ADS. The larger amplitudes for familiar words spoken in the *non-hyper*-IDS - the speech register with exaggerated pitch height and a lower degree of vowel hyperarticulation - lend support for the attentional role of the pitch height feature in IDS. In other words, when infants listen to words to which they are often exposed, their attention towards these words is driven by exaggerated pitch height typical of natural IDS. However, if they listen to words with which they are not familiar, their attention may be driven by hyperarticulated vowels as our results for the *hyper*-ADS condition suggest. It is possible that these infants are at a stage when they are able to distinguish between sounds in their native language and are able to segment words (Jusczyk et al., 1999; Mattys & Jusczyk, 2001; Saffran et al., 1996). Hence, they are more focused on learning new words, exhibiting a lower preference for attentional and affective pitch features of IDS (Newman & Hussain, 2006). Thus, when infants are exposed to new words, their attention to these words is driven by the vowel hyperarticulation feature, which is proposed to play an important linguistic role in infant language acquisition.

Additionally, in contrast to previous studies (Shafer, Shucard, & Jaeger, 1999; Zangl & Mills, 2007) our findings did not demonstrate hemispheric specialisation differences in the processing of words in different speech registers and with different familiarity levels. However, the available research on hemispheric specialisation in infants is limited, so it is difficult to make assumptions about what could influence our findings. One factor that could possibly influence our findings is the presentation of speech stimuli in isolation limiting the IDS prosody on the word level (Zangl & Mills, 2007). Hence, using utterances produced with IDS prosody may be better approach to elicit a hemispheric difference given that infants rarely hear isolated words in everyday life.

It is important to note that previous studies with seven- and nine-month-old infants have shown that early lexical ERP responses in the early time-window investigated in this experiment are not always negative-going deflections (Kidd et al., 2018; Kooijman, Junge, Johnson, Haggort, & Cutler, 2013). Kooijman and colleagues (2013) found that only a small group of infants demonstrated negative responses, while the majority of infants showed a positive response. Also, Kidd and colleagues (2018) demonstrated with a larger sample size (more than 100 infants) that only one-third of tested nine-month-olds exhibited a negative response, with another one-third of infants showing positive responses and the remaining one-third showing responses that are moving from positive to negative signatures (“intermediate responders”) over time. These individual differences in ERPs could very well have an influence on our findings. In future studies with larger sample sizes, it would be instructive to investigate subject variability in the early time-window to shed further light on individual early lexical neurophysiological signatures. For example, it might be possible to further analyse the participant sample in sets of “negative” and “positive” responders.

It should be noted that the generalisability of these results is subject to certain limitations. First, the sample sizes for both age groups in this Chapter are rather small: a common issue in infants’ EEG research due to practical challenges in collecting EEG data from these populations. The second factor that could affect the results of this experiment lies in the word stimuli used. While the experimental design allowed us to control for exaggeration of IDS components, other features such as word stress or vowel quality could influence the findings. Indeed, it has been shown that six-month-old infants acquiring English do not exhibit a preference for predominant stress patterns (strong/weak), while 10-month-old prefer the strong/weak stress pattern even for low-pass filtered words (Jusczyk, Cutler, & Redanz, 1993). Also, future studies could take advantage of the global field power (GFP) or global root mean squares (gRMS) method (Lehmann & Skrandies, 1980) of data analysis. Since this method consists of equalling peaks in the (GFP) data with neural synchronisation periods, thus representing a reference-free indicator of brain activity, it can be especially beneficial in elucidating the factors driving ERP amplitude differences between conditions (Lehmann & Skrandies, 1980).

6.4.1 Conclusion.

Previous research has provided evidence of the distinctive features of IDS, their modifications across infants’ development, as well as behavioural evidence of facilitative effects of these features on infants’ performance on different language tasks and in fostering infants' language acquisition. However, it is important to determine how and when these distinctive IDS features are processed in the first year of language acquisition. In this Chapter, auditory ERPs were recorded from infants to assess the linguistic and attentional effects of pitch height and vowel hyperarticulation features of IDS at the neural level. The results support an important role of exaggerated pitch height in IDS in attracting infants' attention to speech. Additionally, the results provide support for a linguistic role of vowel hyperarticulation in IDS, as evidenced by the facilitative effect of this feature in word processing in 10-month-old infants.

CHAPTER 7

GENERAL DISCUSSION

It is clear from the literature that despite Universal Newborn Screening and the recent practice of hearing device amplification early in life, infants with congenital hearing loss (HL) still demonstrate delays in language development compared to infants with normal hearing (NH) (Moeller et al., 2007a, 2007b; Vohr et al., 2008). This thesis focuses on one particular factor proposed to influence language development: infant-directed speech (IDS). The few studies that have examined IDS to infants with HL have led to contradictory findings; some have found less exaggeration in IDS to infants with HL (Lam & Kitamura, 2010; 2012), and some have not found any differences between IDS to infants with HL and infants with NH (Wieland et al., 2015). This thesis served two overarching aims. The first aim was to add to the state of knowledge by providing a more detailed empirical investigation of the acoustic features in IDS to infants with HL compared to two control groups of infants with NH, one of the same chronological age and the other of the same hearing age. The second aim was to provide a deeper understanding of the potential roles that the acoustic features of IDS may play in early lexical processing.

The results of the four experiments are summarised below and discussed in relation to the objectives of the thesis. This is followed by a discussion of implications for infants with HL, as well as theoretical and practical issues, limitations, and suggestions for future research.

7.1. Summary of key findings

The research objectives of this project were:

1. To examine the acoustic features of IDS to infants with HL as a function of chronological age and hearing experience, and to compare those features to IDS to

infants with NH matched by chronological age and by hearing age (cross-sectional Experiment 1 in Chapter 3);

2. To examine adjustments in IDS features to infants with HL as they acquire more hearing experience during development (longitudinal Experiment 2 in Chapter 4);
3. To examine the role of vowel hyperarticulation and pitch in IDS in lexical processing at the behavioural level in 18-month-old infants with NH (cross-sectional Experiment 3 in Chapter 5);
4. To examine the role of vowel hyperarticulation and pitch in IDS in lexical processing at the neural level in six- and 10-month-old infants with NH (cross-sectional Experiment 4 in Chapter 6).

Objective 1 was addressed in the cross-sectional experiment set out in Chapter 3. With regard to vowel production, it was found that there was no vowel hyperarticulation in IDS to infants with and without HL. This is in line with recent studies that suggest that the vowel hyperarticulation adjustment is not invariably manifested in all cases (Benders, 2013; Dodane & Al-Tamimi, 2007; Englund, 2018; Englund & Behne, 2005; Martin et al. 2015; Wong & Ng, 2018), but contrary to previous studies reporting significant vowel hyperarticulation in IDS to NH infants (Adriaans & Swingley, 2017; Cristia & Seidl, 2014; Kuhl et al., 1997; Tang et al., 2017; Uther et al., 2007), including findings for Australian English (Burnham et al., 2002; Kalashnikova & Burnham, 2018; Kalashnikova et al., 2017; Kalashnikova et al., 2018; Lam & Kitamura, 2010, 2012; Xu et al., 2013). Further phonetic analyses did show that there was increased variability in the production of the vowel /i/ in IDS compared to ADS. However, the general lack of vowel hyperarticulation in these groups could have been a product of the variability introduced by the wide range of ages in each group due to the recognised difficulty of finding and recruiting infants with HL of a particular age.

Despite the lack of overall IDS vs. ADS differences in vowel production, we did find that vowel production in IDS was affected by HL in infants. First, vowel hyperarticulation was moderated by the nature of the HL: mothers *hypo*-articulated vowels in IDS to infants with unilateral HL and *hyper*-articulated vowels in IDS to infants with bilateral HL. Although previous studies showed that infants with unilateral HL have delayed vocabulary development and poorer auditory and language outcomes in comparison to infants with bilateral HL (Fitzpatrick et al., 2019; Välimaa et al., 2018), this is the first study to demonstrate that differences in vowel hyperarticulation in mothers' IDS may be a response to different configurations of infants' HL. Second, greater acoustic distances between the first and second formant frequencies for the vowel /a/ were found in IDS to infants with HL compared to infants with NH matched by hearing age. Since wider separation between the formants for /a/ results in less intelligible speech (Ferguson & Kewley-Port, 2007; Smiljanić & Bradlow, 2009), this may be particularly relevant for the population with HL due to their reliance on F1 properties in vowel discrimination (van Wieringen & Wouters, 1999). This suggests that infants with HL receive less clear speech compared to infants with NH with the same amount of hearing experience.

With regard to prosodic exaggeration in IDS, the results of the first experiment demonstrated heightened pitch and greater pitch variability in IDS compared to ADS with no differences between the three groups of infants. This is in line with findings of heightened pitch and greater pitch variability in IDS compared to ADS (Fernald & Mazzie, 1991; Fernald & Simon, 1984; Grieser & Kuhl, 1988; Kalashnikova & Burnham, 2018). Given previous evidence suggesting an important role of exaggerated pitch in IDS in attracting infants' attention to the speech signal (Cooper & Aslin, 1990; Fernald & Simon, 1984) and facilitating speech processing (Graf Estes & Hurley, 2013; Ma et al., 2011; Thiessen et al., 2005; Trainor & Desjardins, 2002), these results indicate that infants with HL, just like their NH counterparts, receive speech input with prosodic properties beneficial for their language acquisition.

Objective 2*:* In order to further investigate whether maternal IDS production is shaped by infants' linguistic needs, a longitudinal investigation in Chapter 4 assessed adjustments of speech production to infants with HL as a function of increasing hearing experience across infant development. The results showed an absence of vowel hyperarticulation in IDS both to infants with HL and to infants with NH matched by hearing age. The absence of vowel hyperarticulation in IDS to infants with HL confirms the findings of Lam and Kitamura (2010). On the other hand, the absence of vowel hyperarticulation in IDS to infants with NH is in contrast to findings of the presence of vowel hyperarticulation in infants at seven-, nine-, 12-, and 18-months of age (Kalashnikova & Burnham, 2018). The results regarding variability in vowel production in this longitudinal study and in the cross-sectional Experiment 1 extends previous findings. While previous studies demonstrated the presence of greater variability of vowel production in IDS to infants with NH compared to ADS (Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013), the findings here additionally show that this variability in IDS to infants with NH decreases over development along with an increase in formant distances. This suggests that increasingly clear and precise vowel production in IDS across infant development could be related to infants' increasing linguistic experience. Indeed, this was found to be the case: a positive relationship was found between formant distances in mothers' speech and infants' current receptive vocabulary size, extending the previous findings on the relationship between the degree of vowel hyperarticulation in IDS and infants' expressive vocabulary (Hartman et al., 2017; Kalashnikova & Burnham, 2018). Turning to pitch in IDS, it was found that the degree of heightened pitch and pitch variability remained stable across development, both confirming previous findings (Kalashnikova & Burnham, 2018) and showing that the vowel formant modifications in IDS were not generally related to IDS as such, but rather specifically related to infants' linguistic competence.

With regard to the comparison of IDS to infants with HL and infants with NH matched by hearing age, the findings extend previous research (Bergeson, 2011; Lam & Kitamura, 2010; Wieland et al., 2015) indicating a difference in vowel formant production in IDS to these two groups of infants. Whereas variability in formant production decreased for infants with NH over development, there was no difference in formant variability in IDS to infants with HL. Additionally, distances between formants for vowels /i/ and /u/ increased across development in IDS to infants with NH, indicating that these vowels were produced more clearly. However, there was no change across development in the production of formant distances in IDS to infants with HL. These group differences suggest that even after controlling for infants' amount of hearing experience, there are still some differences in vowel production to these infants. Thus, it can be concluded that congenital HL in infants affects maternal production of vowels in IDS.

Objective 3: It was hypothesised that the differences in pitch and vowel production across development may be due different infants' linguistic needs and different roles that these may have in infants' language acquisition. Thus, the goal of the experiment reported in Chapter 5 was to assess the role of vowel hyperarticulation and pitch in lexical processing in 18-month-old infants. The findings indicate that the exaggerated prosody in IDS supports lexical processing even when the vowel hyperarticulation component is absent. This aligns with other findings that IDS prosodic exaggeration facilitates infants' performance on word segmentation, word recognition, and word-learning tasks (Ma et al, 2011; Singh et al., 2009; Thiessen et al., 2005).

Additionally, the results of this experiment suggest that when infants with smaller receptive vocabularies are faced with challenging speech conditions – such as a less preferred speech register (ADS) or IDS that lacks vowel hyperarticulation – their lexical processing performance is poorer as compared to infants with larger receptive vocabularies. This is in line with the finding that 15-month-old infants with larger vocabularies are able to recognise words in a non-native accent (Mulak, Best, Tyler, Kitamura, & Irwin, 2013) while those with smaller vocabularies are not. Such findings suggest that acoustic differences in IDS impact infants' lexical access to a lesser extent when they have larger vocabularies. In contrast, infants achieved successful word recognition when presented with *IDS with vowel hyperarticulation* regardless of their vocabulary size, confirming the findings of Ma et al. (2011) that 21-month-old infants were more successful in learning novel words presented in IDS than in ADS.

Objective 4: The experiment in Chapter 5 assessed lexical processing in 18-month-olds, an age at which infants are already experienced word learners. However, vowel hyperarticulation and pitch might play a unique role in younger infants whose lexicons are at the beginning stage of development. Thus, the main goal of Chapter 6 was to determine whether there is a difference at the neural level in lexical processing between six- and 10-month-old infants for IDS with heightened pitch and vowel hyperarticulation. The results of this experiment demonstrated that when 10-month-old infants listened to unfamiliar words, their lexical processing was driven by vowel hyperarticulation, whereas the recognition of familiar words was driven by heightened pitch in IDS. These findings lend support for the attentional role of pitch in IDS, confirming the previous findings regarding the attentional effects of IDS prosody (Ma et al, 2011; Singh et al., 2009; Thiessen et al., 2005). Additionally, findings regarding lexical processing of unfamiliar words lend support for a linguistic role of vowel hyperarticulation in IDS, confirming the previous studies suggesting that maternal production of clearer vowels in IDS may aid infants in building their lexicons (Kalashnikova & Burnham, 2018; Kuhl et al., 1997).

Taken together, these findings suggest that congenital HL in infants results in a reduction of the usually heightened vowel formant production in maternal IDS compared to IDS to NH counterparts with the same amount of hearing experience. This results in less clear speech to infants with HL, which may affect their receptive vocabulary size. Additionally, these findings indicate that although IDS to NH infants may initially contain greater variability in vowel production compared to ADS, this variability decreases across development accompanied by an increase in the distinctiveness of vowel categories. Furthermore, the results suggest a facilitative effect of both vowel hyperarticulation for word recognition and of pitch in attracting attention to familiar words in 10-month-old infants. However, the facilitative role of vowel hyperarticulation in 18-month-olds' lexical processing is only evident when it occurs together with heightened pitch. Overall, the findings of this thesis indicate that natural IDS with exaggerated prosodic features and exaggerated vowel production represents the richest input beneficial for language acquisition in both infants with HL and NH.

7.2 Implications for infants with HL

Even though mothers adjust IDS to infants with HL to a similar degree as IDS to infants with NH, there are still some differences even when compared to NH infants of the same hearing age. This indicates that HL does have an effect on maternal IDS. This effect is evident in mothers' vowel production, which is discussed in more details in the paragraphs below. On the other hand, the findings indicate that mothers produce adjustments in pitch height and variability in IDS to infants with HL similarly as do mothers of infants with NH. Additionally, this heightened pitch and greater variability remain stable across development. Given that infants with HL display reduced attention to speech (Houston et al., 2003), receiving speech input with exaggerated pitch features may be beneficial for attracting infants' attention to the speech stream. Indeed, research with NH infants has demonstrated the benefits of heightened pitch in IDS in attracting and maintaining infants' attention to the speech input (Cooper & Aslin, 1990; Fernald & Simon, 1984). Thus, it is possible that mothers of infants with HL exaggerate pitch in IDS in response to their infants' greater need for speech properties attractive enough to engage and preserve their attention to the speech input.

CHAPTER 7: GENERAL DISCUSSION

This thesis indicates that the clarity of vowel production in mothers' IDS may be affected by HL in infants. This can have important implications for language acquisition in infants with HL given the findings on the important role of speech clarity on infants' developing linguistic skills. First, it has been demonstrated that the degree of vowel hyperarticulation in IDS to six to eight and 10-12-month-old infants is related to infants' speech perception performance (Liu et al., 2003). Thus, not hearing clear vowels may hinder speech perception in infants with HL. Since better speech perception early in life has been found to predict later language skills (Benasich & Tallal, 2002; Molfese & Molfese, 1985; Molfese, 2000; Tsao, Liu, & Kuhl, 2003), this relation can be extended further, suggesting that decreased clarity in maternal speech may affect different aspects of language acquisition. However, speech perception in infants with HL was not investigated in this project. Thus, future studies may be used to assess the relation of mothers' IDS features and infants' performance on speech perception tasks.

Additionally, it has been found that maternal degree of vowel hyperarticulation in IDS to nine-, 11-, and 15-month-old infants predicts infants' expressive vocabulary growth at both 15- and 19-months of age (Kalashnikova & Burnham, 2018). In line with these previous findings, results from this thesis have demonstrated a relation between formant distances and infants' receptive vocabulary, with larger receptive vocabularies in infants whose mothers produce clearer vowels as measured by distances between the formants. Moreover, the results demonstrate a relation between vowel hyperarticulation and HL infants' expressive vocabulary, with larger expressive vocabularies in HL infants with whose mothers produce more expanded vowels. These findings allow us to advance the argument that receiving speech input with less clear vowel production – as in the case of infants with HL – may hinder infants' receptive and expressive vocabularies. However, our results showed no difference in the receptive and expressive vocabulary size between infants with HL and infants with NH who had comparable amounts of hearing experience, which is contrary to studies that have shown such differences (Moeller et al., 2007a, 2007b; Vohr et al., 2008). Thus, it is possible that while mothers produce less clear vowels in IDS to infants with HL, they use different cues that positively affect infants' vocabularies. Also, this suggests that vowel hyperarticulation may not be essential for processing familiar words as shown in the experiments on lexical processing in this thesis, but it may still play a significant role in the acquisition of new words. Thus, these complex relations between IDS and lexical acquisition require further research.

In addition to the results already discussed, differences were found between IDS to infants with HL and to infants with NH in the production of individual vowels. Previous studies have shown that infants with HL compared to infants with NH display poorer performance on discriminating different vowel contrasts, with vowel place contrasts showing the poorest performance (Eisenberg et al., 2004; Martinez et al., 2008). This thesis shows that maternal production of corner vowels /a, i, u/ is affected by HL in infants. Thus, mothers probably unconsciously adjust their vowel production to their infants' linguistic competence. This is in line with studies that have demonstrated that maternal speech clarity manifested in the degree of vowel hyperarticulation is modulated by infant response to the mother, which is observed in mother-infant dyads where the infant is affected by auditory or sensory processing impairments (Kalashnikova et al., 2018; Lam & Kitamura, 2010, 2012).

These findings contribute to our understanding of IDS qualities to infants with HL by demonstrating that the production of the three corner vowels /a, i, u/ is affected by HL in infants. It could be that exposure to less clear vowel categories results in infants' poorer discrimination of vowel contrasts demonstrated in previous studies (Eisenberg et al., 2004; Martinez et al., 2008). Additionally, this is the first study to demonstrate the relation between exaggeration in vowel production in IDS to infants with HL and their receptive and expressive vocabulary skills at 18 months of age. This suggests that if infants with HL hear clearer vowels then better language outcomes should ensue, specifically at 18 months of age, the age at which the vocabulary spurt typically begins in NH infants. However, the importance of vowel clarity for vocabulary development in infants with HL, and finding that vowel production is affected in speech to these infants together suggest that infants with HL may benefit from parental training aimed in teaching parents to produce clearer vowels. On the other hand, the findings demonstrate no difference in vocabulary sizes between infants with HL and NH suggesting that these infants may use different cues when acquiring spoken language. Further studies should investigate what these possible cues might be.

7.3 Variability in IDS

There are some important theoretical and practical issues related to the study of IDS, the study of language development in infants with HL, as well as the potential roles of IDS features that this thesis has raised. The first theoretical issue concerns the role of variability in vowel production in IDS. Previous studies have demonstrated that even though IDS consists of hyperarticulated vowels, it also shows greater variability in vowel production as compared to ADS (Benders, 2013; Cristia & Seidl, 2014; Englund, 2018; McMurray et al., 2013). It has been assumed that this variability is detrimental for infants' language acquisition since it makes acquisition of vowels more challenging by leading to greater overlap between vowel categories. However, this is in direct contrast with findings that vowel hyperarticulation results in clear vowel categories that facilitate infants' speech perception and vocabulary development (Liu et al., 2003; Kalashnikova & Burnham, 2018). How can these apparently conflicting findings on vowel production in IDS be reconciled? One approach – which was taken in this thesis – is to comprehensively investigate this issue by employing a battery of different measures of vowel production. This allows for a more precise picture of between- and within-category variability in IDS. Another possibility is to assess variability in vowel production across infant development. This thesis showed that although IDS to infants with NH initially contains greater variability at eight months of age, there is a decrease in this variability at 15 months of age along with an increase in the precision of vowel realisation. Thus, it is possible that increasing linguistic competence leads to a concurrent increase in vowel clarity, and that mothers thus adjust their IDS according to infants' linguistic need for vowel clarity to build their vocabularies. Thus, in assessing variability in vowel production in IDS, it is important to take into account individual infants' current stage of language acquisition.

Additionally, in order to make conclusions regarding the possible effects of vowel variability in IDS, the role of this variability on infants' performance on tasks such as lexical processing and speech perception should be examined. Although this thesis has demonstrated greater variability in vowel production in IDS compared to ADS, this variability was not taken into account in Experiments 3 and 4, which focused on the effects of vowel hyperarticulation and pitch on infants' lexical processing. This focus was determined a priori given that previous evidence has identified vowel hyperarticulation and heightened pitch as the two IDS components that can potentially facilitate lexical processing (Graf Estes & Hurley, 2013; Ma et al., 2011; Song et al., 2010). Future studies should directly investigate the role of variability in vowel production on infant on-line speech processing at different ages or stages of language acquisition to clearly understand how this feature is related to infants' linguistic competence.

7.4 Limitations and future research

In the first part of this thesis, we were interested in how mothers adjust their IDS to infants with HL. While we were able to control for infants' hearing experience by including a hearing age-matched control group, we were unable to control for potential individual differences in residual hearing in the group of infants with HL, or for their hearing ability at the time of testing. These differences can impact infants' later language outcomes (Nicholas & Geers, 2006; Szagun, 2001, 2004), and they could further inform the adaptations to IDS that mothers make in relation to their infants' individual perceptual and processing needs. As we did not have access to this information enclosed in participants' medical records, this is left as an issue for future research to address.

We also acknowledge that in this study we were unable to recruit infants from a defined narrow age range resulting in a wide age range in all three groups of infants. This was due to the difficulty of recruiting infants with congenital HL. Furthermore, we were unable to recruit equal numbers of infants with unilateral and bilateral HL, or of those implanted with Cochlear Implants and those fitted with Hearing Aids. Nevertheless, our exploratory analyses of these sub-groups suggest that hearing configuration – unilateral versus bilateral HL – may impact IDS qualities to infants with HL. Given the small sample sizes, however, future studies will need to include the configuration of HL (unilateral or bilateral) as a factor in the study design. No previous studies have compared IDS features in infants with unilateral versus bilateral HL, but it warrants further investigation since findings suggest a difference in the rate of language development between infants with unilateral and bilateral HL and since the experiment in this thesis indicates a difference in the vowels spoken to these infants.

Moving from differences to similarities in IDS production to infants with HL and infants with NH, the finding that infants with HL in this study were exposed to IDS with similar acoustic properties to that to their peers with NH suggests that despite degraded input pre-intervention, these infants are still spoken to in IDS with features that may benefit their language acquisition. Given the fundamental role of early speech input quantity and quality on predicting infants' language outcomes (Hartman et al., 2017; Kalashnikova & Burnham, 2018; Liu et al., 2003), these findings further support the need for early screening, treatment, and intervention, and a focus on speech perception and parent-infant communication to optimise the early linguistic experiences of infants born with congenital HL (Ching et al., 2013; Moeller & Tomblin, 2015; Niparko et al., 2010). However, some differences persist, and these differences may have implications for speech intelligibility and later language development in this population. Further research that involves controlling for infants' residual hearing, HL configuration and fitting device is required to fully understand the source of these adjustments in mothers' IDS, and the implications they may have for these infants' language development.

Additionally, in order to understand the specific roles that the acoustic features of IDS may play in language acquisition of infants with HL and to investigate whether these infants employ different cues from infants with NH to navigate their language input and acquire the phonemic and lexical inventories of their language, an assessment of their performance in language processing tasks is required.

Finally, we acknowledge the differences in experimental strategies adopted for this thesis. Specifically, the first two experiments focused on comparing groups of infants with and without HL, whereas the third and the fourth experiment kept the populations constant but instead focused on manipulating stimulus properties and on assessing their effects on infants' lexical processing performance. This was done in order to be able to identify the qualities of IDS to infants with HL as compared to infants with NH (Experiment 1, Experiment 2), but also to be able to disentangle the role of particular IDS features on language processing (Experiment 3, Experiment 4). The benefit of this approach is that it made it possible to directly assess the role of specific IDS features in isolation and in combination. This approach could be useful in future research that involves hard-to-find populations of infants, or in research that tries to disentangle the effects of individual qualities of IDS on infants' performance on various language-processing tasks. While it has benefits, we acknowledge that this approach has its limitations as well, including the manipulation of speech stimuli instead of using natural speech input. Additionally, limiting the testing of lexical processing to infants with NH only may tell us about the role of specific IDS features in their lexical processing, but may not necessarily imply that the same is the case for infants with HL.

7.5 Concluding Remarks

Building on previous research that has found an effect of infant behaviour or processing differences on the nature of IDS to infants with NH (Kalashnikova et al., 2018; Lam & Kitamura, 2012), and effects of the nature of IDS on later language development, this thesis has shown that hearing status of the infant impacts mothers' IDS, and this in turn, impacts language development. It could be that infants' lack of vowel discrimination due to their HL signals to the mother to keep distances between formants large (in case of vowel /a/) or smaller (in case of /i/ and /u/). Thus, mothers adjust their IDS in response to the infant's linguistic competence and needs. However, the less clear vowel production in IDS to infants with HL shown in this study does not have a detrimental effect on their receptive vocabulary indicating a possible use of different acoustic cues as didactic features in IDS to infants with HL. Additionally, the findings from this thesis suggest a facilitative role of vowel hyperarticulation in lexical processing in infants with smaller lexicons (10-month-olds) and an attentional role of pitch in IDS in younger infants. With regard to older infants, this thesis suggests a reliance on vowel hyperarticulation as a cue in lexical processing only in infants with smaller receptive vocabularies. Overall, these findings suggest that individual components of IDS may play different attentional and linguistic roles depending on infants' linguistic competence and individual linguistic and perceptual needs.

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Appendix A: Information Sheets and Consent Forms

Seeds of Language Development

the MARCS institute for brain, behaviour and development — THE HEARing CRC® — WESTERN SYDNEY UNIVERSITY

INFORMATION SHEET FOR RESEARCH PARTICIPATION

Project Title: Seeds of language development: Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

Support for this study: HEARing Cooperative Research Centre
Western Sydney University

Invitation to Participate and Description of Project
You are invited to take part in a study to investigate infants' language development and hearing loss. The study is funded by the Hearing Cooperative Research Centre and led by Professor Denis Burnham and Dr Marina Kalashnikova. The aim of this study is to observe how young infants perceive the sound patterns of their native language. This study will take place at the Shepherd Centre where your child has regular appointment.

What does the study involve?
If you choose to take part in this study, you will be asked to fill out a questionnaire about you and your child. Your child will sit in a comfortable chair or on your lap in front of a monitor. During the session, your child will see images presented on a screen and listen to sounds presented over loudspeakers. We will record when and for how long your child looks at the screen and/or his/her responses. There will also be a short play and parent-child interaction segment in which you will be recorded as you talk to your child.

A staff member will monitor the session on a television monitor connected to a video camera focused on your infant. We will videotape the session for later verification of your infant's responses to the sounds. The study will last around 30 minutes and it will be concluded if your child becomes fussy, or if you wish to finish.

How much time will the study take?
The study is approximately 30 minutes long.

Will the study involve any discomfort for me or my child?
The study is not intended to involve any discomfort to you or your child. If your child becomes restless during the study, we will stop immediately.

Will the study benefit me?
While there may not be any specific immediate benefits to any individual, benefits of this research include: the possibility of identifying the aspects of language acquisition that predict later language delay associated with hearing loss; researchers developing new devices; clinicians developing new intervention and remediation strategies; and early intervention, education and clinical end-users providing (re)habilitation services.

How is this study being paid for?

1 of 3

Appendix A-1. *Information Sheet for experiments presented in Chapters 3 and 4 (page 1 of 2)*

Seeds of Language Development

This study is being supported by the HEARing Cooperative Research Centre (HEARing CRC) and internal funding from Western Sydney University. Your child will receive a small gift and a BabyLab scientific degree at the end of the study.

Will anyone else know the results? How will the results be disseminated?

The research team will report the results at conferences and in academic journals. All information about the participants will remain confidential. If you would like to know about the results, we can send them to you once the study is completed.

Excerpts from the recordings may also be used for illustrative purposes in teaching, in conference presentations or in various relevant electronic media but neither you nor your child will be identified if the recordings are used for any of these purposes.

Confidentiality

Personal information gathered in the course of the study is confidential and will be securely stored. No personal information will be given to any persons other than the researchers unless it is made anonymous.

Can I withdraw from the study?

Participation is entirely voluntary: you are not obliged to be involved and, if you do participate, you can withdraw at any time without giving any reason and without any consequences.

Can I tell other people about the study?

Yes please, you can tell other people about the study and they can contact the MARCS BabyLab (Scott O'Loughlin or Maria Christou-Ergos on 9772 6696) to register their interest.

What if I require further information?

When you have read this information, we will discuss it with you further and answer any questions you may have. Please feel free to ask about anything you don't understand and to consider this consent form for as long as you feel is necessary before you decide whether to participate.

If you would like to know more at any stage of the study, please contact us. We will be happy to discuss it with you:

Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

What if I have a complaint?

This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H11517.

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email HumanEthics@westernsydney.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

2 of 3

Appendix A-1. *Information Sheet for experiments presented in Chapters 3 and 4 (page 2 of 2)*

Seeds of Language Development

CONSENT FORM for RESEARCH PARTICIPATION

Project Title: Seeds of language development: Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

1. I agree to take part in the Seeds of Language Development study as described in the Information Sheet.

2. I have read the Information Sheet for Research Participants. This Information Sheet tells me what the research is for, and what participants do in the study.

3. I have had a chance to ask questions. I was given complete answers to my questions.

4. I understand that the researcher may contact the clinic for the hearing loss record of my child.

5. I agree to release my child's hearing loss clinical record to be kept in this project.

6. I can withdraw from the study at any time. If I withdraw from the study, I understand that Western Sydney University will not discriminate against me in the future.

7. The results can be published and the results can be presented. I will be identified only by an identification code. My name will not be used in research presentations or publications.

8. I agree to be contacted for participation in future research project. YES / NO

9. If I have questions, I can contact

    Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
    Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
    Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

10. I am keeping a copy of this information sheet and consent form.

Name (please PRINT) ______________________________

Signature: ______________________________

Date: ______________________________

3 of 3

Appendix A-2. *Consent Form for experiments presented in Chapters 3 and 4 (page 1 of 2)*

Seeds of Language Development
Signature of Person Obtaining Consent Phone

_______________________________ _______________________________

Note: This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H11517. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email HumanEthics@westernsydney.edu.au.
Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

4 of 3

Appendix A-2. *Consent Form for experiments presented in Chapters 3 and 4 (page 2 of 2)*

Seeds of Language Development

INFORMATION SHEET FOR RESEARCH PARTICIPATION

Project Title: Seeds of language development: Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

Support for this study: HEARing Cooperative Research Centre
Western Sydney University

Invitation to Participate and Description of Project
You are invited to take part in a study to investigate infants' language development and hearing loss. The study is funded by the Hearing Cooperative Research Centre and led by Professor Denis Burnham and Dr Marina Kalashnikova. The aim of this study is to observe how young infants perceive different speech registered via the eye tracking procedure. This study will take place at the MARCS Institute Baby Lab.

What does the study involve?
If you choose to take part in this study, you will be asked to fill out a questionnaire about you and your child. Your child will sit in a comfortable chair or on your lab in front of a monitor to watch and listen to the VDO display. During the session, we will measure your child's eye movements and record them to a computer using a Tobii eye tracker system. This system is certified for use with infants and children, and it is used extensively in infant and child testing. These procedures are completely painless and are regularly used with babies. There will also be a short play and parent-child interaction segment in which you will be recorded as you talk to your child. The study will last around 30 minutes and will be concluded if your child becomes fussy, or if you wish to finish.

How much time will the study take?
The study is approximately 30 minutes long.

Will the study involve any discomfort for me or my child?
The study is not intended to involve any discomfort to you or your child. The only risk is for your child to experience some boredom or restlessness, in which case we would stop immediately.

Will the study benefit me?
There will not be any specific immediate benefits to any individual. Benefits of this research include: the possibility of identifying the aspects of language acquisition that predict later language delay associated with hearing loss; researchers developing new devices; clinicians developing new intervention and remediation strategies; and early intervention, education and clinical end-users providing (re)habilitation services.

How is this study being paid for?
This study is being supported by the HEARing Cooperative Research Centre (HEARing CRC) and internal funding from Western Sydney University. Your child will receive a small gift and a BabyLab scientific degree at the end of the study.

1 of 3

Appendix A-3. *Information Sheet for experiment presented in Chapter 5 (page 1 of 2)*

Will anyone else know the results? How will the results be disseminated?
The research team will report the results at conferences and in academic journals. All information about the participants will remain confidential. If you would like to know about the results, we can send them to you once the study is completed.
Excerpts from the recordings may also be used for illustrative purposes in teaching, in conference presentations or in various relevant electronic media but neither you nor your child will be identified if the recordings are used for any of these purposes.

Confidentiality
Personal information gathered in the course of the study is confidential and will be securely stored. No personal information will be given to any persons other than the researchers unless it is made anonymous.

Can I withdraw from the study?
Participation is entirely voluntary: you are not obliged to be involved and, if you do participate, you can withdraw at any time without giving any reason and without any consequences.

Can I tell other people about the study?
Yes please, you can tell other people about the study and they can contact the MARCS BabyLab (Scott O'Loughlin or Maria Christou-Ergos on 9772 6696) to register their interest.

What if I require further information?
When you have read this information, we will discuss it with you further and answer any questions you may have. Please feel free to ask about anything you don't understand and to consider this consent form for as long as you feel is necessary before you decide whether to participate.

If you would like to know more at any stage of the study, please contact us. We will be happy to discuss it with you:

Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

What if I have a complaint?
This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H11517.

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email HumanEthics@westernsydney.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

Appendix A-3. *Information Sheet for experiment presented in Chapter 5 (page 2 of 2)*

Seeds of Language Development

CONSENT FORM for RESEARCH PARTICIPATION

Project Title: Seeds of language development: Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

1. I agree to take part in the Seeds of Language Development study as described in the Information Sheet.

2. I have read the Information Sheet for Research Participants. This Information Sheet tells me what the research is for, and what participants do in the study.

3. I have had a chance to ask questions. I was given complete answers to my questions.

4. I can withdraw from the study at any time. If I withdraw from the study, I understand that Western Sydney University will not discriminate against me in the future.

5. The results can be published and the results can be presented. I will be identified only by an identification code. My name will not be used in research presentations or publications.

6. I agree to be contacted for participation in future research project. YES / NO

7. If I have questions, I can contact

Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

10. I am keeping a copy of this information sheet and consent form.

Name (please PRINT) ____________________

Signature: ____________________

Date: ____________________

3 of 3

Appendix A-4. *Consent Form for experiment presented in Chapters 5 (page 1 of 2)*

Seeds of Language Development
Signature of Person Obtaining Consent Phone

______________________________ ______________________________

Note: This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H11517. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email HumanEthics@westernsydney.edu.au.
Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

4 of 3

Appendix A-4. *Consent Form for experiment presented in Chapter 5 (page 2 of 2)*

Seeds of Language Development

INFORMATION SHEET FOR RESEARCH PARTICIPATION

Project Title: **Seeds of language development: Development of hearing impaired infants' speech perception and vocalisation over the first three years of life**

Support for this study: HEARing Cooperative Research Centre
Western Sydney University

Invitation to Participate and Description of Project
You are invited to take part in a study to investigate infants' language development and hearing impairment. The study is funded by the Hearing Cooperative Research Centre and led by Professor Denis Burnham and Dr Marina Kalashnikova. The aim of this study is to observe how young infants perceive different speech registered via the electroencephalogram (EEG) procedure.

What does the study involve?
If you choose to take part in this study, you will be asked to fill out a questionnaire about you and your child. Your child will sit in a comfortable chair or on your lab in front of a monitor. During the session, we will measure your child's brain waves and record them to a computer using an advanced EEG system called a geodesic sensor net. This involves putting a smooth net of sensors on your child's head before testing begins. The net takes only a few minutes to put on, and most children quickly forget they are wearing it. This system is certified for use with infants and children, and it is used extensively in infant and child testing. These procedures are completely painless and are regularly used with babies. The study will last around 20 minutes and will be concluded if your child becomes fussy, or if you wish to finish.

How much time will the study take?
The study is approximately 20 minutes long.

Will the study involve any discomfort for me or my child?
The study is not intended to involve any discomfort to you or your child. The only risk is for your child to experience some boredom or restlessness, in which case we would stop immediately.

Will the study benefit me?
There will not be any specific immediate benefits to any individual. Benefits of this research include: the possibility of identifying the aspects of language acquisition that predict later language delay associated with hearing loss; researchers developing new devices; clinicians developing new intervention and remediation strategies; and early intervention, education and clinical end-users providing (re)habilitation services.

How is this study being paid for?
This study is being supported by the HEARing Cooperative Research Centre and internal funding from Western Sydney University. You will be compensated $30 for your travel expenses at each visit.

1 of 3

Appendix A-5. *Information Sheet for experiment presented in Chapter 6 (page 1 of 2)*

Seeds of Language Development

Will anyone else know the results? How will the results be disseminated?
The research team will report the results at conferences and in academic journals. All information about the participants will remain confidential. If you would like to know about the results, we can send them to you once the study is completed.
Excerpts from the recordings may be used also be used for illustrative purposes in teaching, in conference presentations or in various relevant electronic media but neither you nor your child will be identified if the recordings are used for any of these purposes.

Confidentiality
Personal information gathered in the course of the study is confidential and will be securely stored. No personal information will be given to any persons other than the researchers unless it is made anonymous.

Can I withdraw from the study?
Participation is entirely voluntary: you are not obliged to be involved and, if you do participate, you can withdraw at any time without giving any reason and without any consequences.

Can I tell other people about the study?
Yes please, you can tell other people about the study and they can contact the BabyLab on (02) 9772 6696 to register their interest.

What if I require further information?
When you have read this information, we will discuss it with you further and answer any questions you may have. Please feel free to ask about anything you don't understand and to consider this consent form for as long as you feel is necessary before you decide whether to participate.

If you would like to know more at any stage of the study, please contact us. We will be happy to discuss it with you:

Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

What if I have a complaint?
This study has been approved by the University of Western Sydney Human Research Ethics Committee. The Approval number is H11517.

If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email humanethics@westernsydeny.edu.au.

Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

2 of 3

Appendix A-5. *Information Sheet for experiment presented in Chapter 6 (page 2 of 2)*

Seeds of Language Development

<u>CONSENT FORM for RESEARCH PARTICIPATION</u>

Project Title: **Seeds of language development: Development of hearing impairedinfants' speech perception and vocalisation over the first three years of life**

1. I agree to take part in the Seeds of Language Development study as described in the Information Sheet.

2. I have read the Information Sheet for Research Participants. This Information Sheet tells me what the research is for, and what participants do in the study.

3. I have had a chance to ask questions. I was given complete answers to my questions.

4. I can withdraw from the study at any time. If I withdraw from the study, I understand that Western Sydney University will not discriminate against me in the future.

5. The results can be published and the results can be presented. I will be identified only by an identification code. My name will not be used in research presentations or publications.

6. I agree to be contacted for participation in future research project. YES / NO

7. If I have questions, I can contact

    Professor Denis Burnham, (02) 9772 6677; d.burnham@westernsydney.edu.au
    Dr Marina Kalashnikova, (02) 9772 6264; m.kalashnikova@westernsydney.edu.au
    Dr Benjawan Kasisopa, (02) 9772 6269; b.kasisopa@westernsydney.edu.au

8. I am keeping a copy of this information sheet and consent form.

Name (please PRINT) ______________________________

Signature: ______________________________

Date: ______________________________

3 of 3

Appendix A-6. *Consent Form for experiment presented in Chapter 6 (page 1 of 2)*

Seeds of Language Development
Signature of Person Obtaining Consent Phone

_______________________________ _________________________

Note: This study has been approved by the Western Sydney University Human Research Ethics Committee. The Approval number is H11517. If you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee through the Office of Research Services on Tel 02 4736 0883 Fax 02 4736 0013 or email humanethics@westernsydeny.edu.au.
Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

4 of 3

Appendix A-6. *Consent Form for experiment presented in Chapter 6 (page 2 of 2)*

CONSENT TO DISCLOSE MEDICAL INFORMATION

Project Title: Seeds of language development: Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

I (Parent/Guardian name) ____

Of (home address) ____

____

Authorise and consent to the collection, disclosure or release of any relevant written or verbal personal hearing loss information to any person who provides a medical service, hospital service, occupational rehabilitation service, independent medical examination including the treating practitioners (for example: treating doctors, counsellors, audiologists, health practitioners or other medical specialists) to my child (child's name ______________________________ ______________________________) in connection with the hearing loss of my child.

I understand and confirm that upon request by the researcher and its authorised representatives that this information regarding the provision of a medical service relevant to my child's hearing loss may be obtained. This information will be treated confidentially and only used to assess my child hearing ability relevant to the participated studies.

Signature: ______________________________

Date: ______________________________

Signature of Person Obtaining Consent   Phone

______________________________   ______________________________

Appendix A-7. *Consent Form for disclosure of medical information for parents of infants with HL (Chapters 3 and 4)*

Appendix B: Questionnaire

Participant ID:……………………………

Seeds of Language Development
Development of Speech Perception and Vocalisation of Infant with Hearing Loss over the First Three Years of Life

Infant's name: ________________________________ **Infant's Date of Birth:** ________________

Part A-Participant Information

Parent 1's Age (today): _______ Parent 2's Age (today): _______

*Parent 1's Name: ________________________ *Parent 2's Name: ________________________

*Parent 1's Occupation: ____________________ *Parent 2's Occupation: ____________________

*Parent 1's Education (Please circle both secondary and tertiary level completed):

Secondary Education: Year 10 Year 11 Year 12

Tertiary Education: TAFE University Masters Ph.D. Other_______________

*Parent 2's Education (Please circle both secondary and tertiary level completed):

Secondary Education: Year 10 Year 11 Year 12

Tertiary Education: TAFE University Masters Ph.D. Other_______________

*Please indicate the details of the area you live in: Suburb____________________ Post code: ________

1. Were there any complications of Pregnancy ____
and/or Labour/Delivery ____
2. Have you ever been diagnosed with Postnatal Depression (PND)? Yes ☐ No ☐
3. Was your infant: Fullterm 38-42 weeks ☐ Premature < 37 weeks ☐.……...weeks Post-mature >42 weeks ☐
4. What was your infant's (a) Birthweight? __________ kg (b) Apgar score? ________ (0-10)
5. Did your infant complete the newborn hearing screen? Yes ☐ No ☐

5a. Degree of hearing loss (current): Left ear: __________________ Right ear: __________________

5b. Configuration of hearing loss: Left side ☐ Right side ☐ Both sides ☐

5c. Etiology____

5d.Type of hearing device (e.g. hearing aid model, Cochlear Implant, etc.): Left ear : ________________________ Right ear: ______________________

Office Use	ID Number: ………………………

Appendix B-1. *Participant Information Questionnaire (page 1 of 2)*

Participant ID:……………………………

5e. When was the first time the hearing device fitted?____________________

5f. When was your infant's last visit to an audiology clinic/ hearing related specialist?_____________

Were any changes made to the hearing device(s) settings? (please describe) _________________

____

____

____

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

____

____

____

7. In your child's family is there a history of Hearing loss/deafness Yes ☐ No ☐

If yes, relation to child? ______________________ Type/Degree? _____________________

<u>Part B-Language Information</u>

8. Is there a history of reading, speech or language problems (e.g., dyslexia) in your family? Yes ☐ No ☐

If yes, relation to child? _______________________Type/Degree?_________________________

9. What is the primary language spoken in your home? ______________________________________

Parent 1's first language ___________________ Parent 2's first language _____________________

Please list any other languages/accents (including English accents) that are spoken in your home:

1. ________________________________ Hours/week spoken?____________________________

2. ________________________________ Hours/week spoken?____________________________

3. ________________________________ Hours/week spoken?____________________________

10. What is the mode of communication that you and other caregivers use with the child (e.g., oral language, sign language, combination of oral language and signs, etc.). Please describe:___________

____

____

____

Office Use	ID Number: ………………………

Appendix B-1. *Participant Information Questionnaire (page2 of 2)*

Appendix C: Stimuli used in the experiment presented in Chapter 5

Table C. 1. *Acoustic analysis of the target words in hyper-IDS condition*

Stimuli	F0	F1	F2
Look at the book	304.26	794.09	1749.99
Look at the car	273.52	941.40	1515.26
Look at the cup	364.12	932.35	1399.70
Look at the key	288.14	367.78	1402.46
Look at the sheep	306.11	588.62	2939.44
Look at the shoe	283.93	504.03	1851.74
Where is the book	351.81	719.01	1168.57
Where is the car	395.23	888.19	1566.11
Where is the cup	303.20	774.53	999.79
Where is the key	373.46	376.94	1470.01
Where is the sheep	253.04	428.69	2912.29
Where is the shoe	271.38	345.89	1803.02

Table C. 2. *Acoustic analysis of the target words in non-hyper-IDS condition*

Stimuli	F0	F1	F2
Look at the book	151.24	141.98	909.98
Look at the car	225.24	836.52	1283
Look at the cup	245.94	648.42	1161.67
Look at the key	302.26	307.06	1426.5
Look at the sheep	144.23	355.28	1564.63
Look at the shoe	294.03	318.43	1956.42
Where is the book	135.01	235.74	927.75
Where is the car	225.60	817.13	1089.14
Where is the cup	250.11	529.27	1041.47
Where is the key	303.77	305.83	1478.02
Where is the sheep	141.01	327.08	2685.75
Where is the shoe	294.94	320.62	1974.75

Table C. 3. *Acoustic analysis of the target words in hyper-ADS condition*

Stimuli	F0	F1	F2
Look at the book	248	478.85	981.79
Look at the car	227.91	915.90	1439.92
Look at the cup	328.63	1048.92	1365.23
Look at the key	233.16	339.06	2943.93
Look at the sheep	255.40	266.18	2879.31
Look at the shoe	248.95	323.64	1692.11
Where is the book	312.37	456.25	1003.40
Where is the car	209.66	1050.19	1490.81
Where is the cup	241.89	1011.97	1308.40
Where is the key	218.96	338.91	2880.40
Where is the sheep	237.05	378.24	2978.71
Where is the shoe	234.65	324.71	1715.40

Appendix D: Stimuli used in the experiment presented in Chapter 6

Table D. 1. *Acoustic analysis of the familiar words in hyper-IDS condition*

Stimuli	F0
bed	255.92
bird	270.13
book	378.01
car	298.26
dog	278.24
eye	263.13
keys	290.79
milk	297.39
mouth	218.52
nappy	239.55

Table D. 2. *Acoustic analysis of the unfamiliar words in hyper-IDS condition*

Stimuli	F0
bias	294.55
blame	254.82
board	246.42
clutch	365.44
code	291.45
dent	314.16
domain	242.10
maze	252.75
morph	250.90
oak	308.30

Table D. 3. *Acoustic analysis of the familiar words in non-hyper-IDS condition*

Stimuli	F0
baby	228.10
bath	250.15
chair	237.25
doll	245.90
duck	302.17
hand	214.73
hat	347.03
pram	260.01
sock	432.67
toy	246.30

Table D. 4. *Acoustic analysis of the unfamiliar words in non-hyper-IDS condition*

Stimuli	F0
bow	223.20
brand	219.11
calf	248.60
dorm	263.68
doubt	247.31
hook	311.15
host	221.23
pest	274.65
skill	226.17
tax	368.97

Table D. 5. *Acoustic analysis of the familiar words in hyper-ADS condition*

Stimuli	F0
ball	163.57
bottle	150.78
brush	183.08
cat	165.58
cup	270.66
door	178.81
foot	330.48
juice	204.42
nose	157.57
shoe	181.17

Table D. 6. *Acoustic analysis of the unfamiliar words in hyper-ADS condition*

Stimuli	F0
barrel	172.54
bay	178.20
breed	182.92
clone	182.45
court	206.83
dove	186.13
flood	184.35
judge	170.74
nerve	180.80
shrub	189.10

Appendix E: Detailed results of ANOVAs presented in Chapter 6

Results of 3 Speech (*hyper*-IDS, *non-hyper*-IDS, *hyper*-ADS) x 2 Familiarity (familiar, unfamiliar) x 4 anterior-posterior Electrode Site (Frontal, Central, Parietal, Occipital) x 2 Hemispheric Specialisation (left, right) repeated-measures ANOVAs

250-500ms time-window: 6-month-olds.

Table E. 1. *The results of Results of 3 Speech x 2 Familiarity x 4 Electrode Site x 2 Hemispheric Specialisation repeated-measures ANOVA*

Effect	df	F	p	η_p^2
Speech	2, 24	1.51	= .24	.11
Familiarity	1, 12	.15	= .70	.01
Electrode site	3, 36	51.24	**< .001**	.81
Hemispheric Specialisation	1, 12	7.61	**= .02**	.39
Speech x Familiarity	2, 24	2.19	= .13	.16
Speech x Electrode site	6, 72	1.31	= .29	.10
Familiarity x Electrode site	3, 36	.63	= .54	.05
Speech x Familiarity x Electrode Site	6, 72	.44	= .62	.04
Speech x Hemispheric specialisation	2, 24	.49	= .62	.04
Familiarity x Hemispheric Specialisation	1, 12	.86	= .37	.07
Speech x Familiarity x Hemispheric Specialisation	2, 24	2.60	= .10	.18
Electrode Site x Hemispheric Specialisation	3, 36	2.80	= .06	.19
Speech x Electrode Site x Hemispheric Specialisation	6, 72	1.10	= .36	.08
Familiarity x Electrode Site x Hemispheric Specialisation	3, 36	.57	= .57	.05
Speech x Familiarity x Electrode Site x Hemispheric Specialisation	6, 72	1.24	= .31	.09

Post-hoc Bonferroni analyses.

Table E. 2. *The means and standard errors (SE) for the main effect of the Electrode Site*

Electrode Site	Mean	SE
Frontal	2.13	.52
Central	1.04	.45
Parietal	- .48	.39
Occipital	- 1.68	.22

Table E. 3. *Pairwise Comparisons for the main effect of the Electrode Site*

Electrode Site 1	Electrode Site 2	Mean Difference (1-2)	SE	*p*
Frontal	Central	1.09	.18	**< .001**
	Parietal	2.61	.39	**< .001**
	Occipital	3.81	.46	**< .001**
Central	Frontal	- 1.09	.18	**< .001**
	Parietal	1.52	.23	**< .001**
	Occipital	2.72	.29	**< .001**
Parietal	Frontal	- 2.61	.39	**< .001**
	Central	- 1.52	.23	**< .001**
	Occipital	1.20	.29	**= .01**
Occipital	Frontal	- 3.81	.46	**< .001**
	Central	- 2.72	.36	**< .001**
	Parietal	- 1.20	.29	**= .01**

Table E. 4. *The means and standard errors (SE) for the main effect of Hemispheric Specialisation*

Hemispheric Specialisation	Mean	SE
Left	.53	.35
Right	- .02	.39

Table E. 5. *Pairwise Comparisons for the main effect of the Hemispheric Specialisation*

Hemispheric Specialisation 1	Hemispheric Specialisation 2	Mean Difference 1-2	SE	*p*
Left	Right	.55	.20	**= .02**
Right	Left	- .55	.20	**= .02**

600-900ms time-window: 6-month-olds.

Table E. 6. *The results of Results of 3 Speech x 2 Familiarity x 4 Electrode Site x 2 Hemispheric Specialisation repeated-measures ANOVA*

Effect	df	F	*p*	η_p^2
Speech	2, 24	1.18	= .33	.09
Familiarity	1, 12	1.38	= .26	.10
Electrode site	3, 36	2.97	= .09	.20
Hemispheric Specialisation	1, 12	1.23	= .29	.09
Speech x Familiarity	2, 24	.384	= .68	.03
Speech x Electrode site	6, 72	2.49	= .09	.17
Familiarity x Electrode site	3, 36	1.26	= .30	.10
Speech x Familiarity x Electrode Site	6, 72	.85	= .42	.07
Speech x Hemispheric Specialisation	2, 24	1.67	= .21	.12
Familiarity x Hemispheric Specialisation	1, 12	.04	= .84	.01
Speech x Familiarity x Hemispheric Specialisation	2, 24	2.81	= .08	.19
Electrode Site x Hemispheric Specialisation	3, 36	.58	= .59	.05
Speech x Electrode Site x Hemispheric Specialisation	6, 72	.71	= .55	.06
Familiarity x Electrode Site x Hemispheric Specialisation	3, 36	.40	= .66	.03
Speech x Familiarity x Electrode Site x Hemispheric Specialisation	6, 72	.641	= .61	.05

250-500ms time-window: 10-month-olds.

Table E. 7. *The results of Results of 3 Speech x 2 Familiarity x 4 Electrode Site x 2 Hemispheric Specialisation repeated-measures ANOVA*

Effect	df	F	p	η_p^2
Speech	2, 30	.01	= .99	.01
Familiarity	1, 15	3.09	= .10	.17
Electrode site	3, 45	16.59	**< .001**	.52
Hemispheric Specialisation	1, 15	.01	= .10	.01
Speech x Familiarity	2, 30	7.40	**= .01**	.33
Speech x Electrode site	6, 90	2.63	= .07	.15
Familiarity x Electrode site	3, 45	.94	= .39	.06
Speech x Familiarity x Electrode Site	6, 90	2.70	= .06	.15
Speech x Hemispheric Specialisation	2, 30	2.92	= .07	.16
Familiarity x Hemispheric Specialisation	1, 15	1.54	= .23	.09
Speech x Familiarity x Hemispheric Specialisation	2, 30	.91	= .41	.06
Electrode Site x Hemispheric Specialisation	3, 45	1.79	= .19	.11
Speech x Electrode Site x Hemispheric Specialisation	6, 90	1.18	= .32	.07
Familiarity x Electrode Site x Hemispheric Specialisation	3, 45	.21	= .84	.01
Speech x Familiarity x Electrode Site x Hemispheric Specialisation	6, 90	.45	= .76	.03

Post-hoc Bonferroni analyses.

Table E. 8. *The means and standard errors (SE) for the main effect of the Electrode Site*

Electrode Site	Mean	SE
Frontal	.54	.48
Central	- .06	.41
Parietal	- .74	.34
Occipital	- 1.41	.26

Table E. 9. *Pairwise Comparisons for the main effect of the Electrode Site*

Electrode Site 1	Electrode Site 2	Mean Difference (1-2)	SE	*p*
Frontal	Central	.60	.23	= .13
	Parietal	1.28	.02	**= .02**
	Occipital	1.95	.01	**= .01**
Central	Frontal	- .60	.23	**= .13**
	Parietal	.68	.19	**= .02**
	Occipital	1.35	.30	**= .01**
Parietal	Frontal	- 1.28	.37	**= .02**
	Central	- .68	.19	**= .02**
	Occipital	.67	.22	= .06
Occipital	Frontal	- 1.95	.38	**= .01**
	Central	- 1.35	.30	**= .01**
	Parietal	- .67	.22	= .06

600-900ms time-window: 10-month-olds.

Table E. 10. *The results of Results of 3 Speech x 2 Familiarity x 4 Electrode Site x 2 Hemispheric Specialisation repeated-measures ANOVA*

Effect	df	F	*p*	η_p^2
Speech	2, 30	1.48	= .24	.09
Familiarity	1, 15	.03	= .87	.01
Electrode site	3, 45	.22	= .70	.02
Hemispheric Specialisation	1, 15	.51	= .49	.03
Speech x Familiarity	2, 30	4.86	**= .02**	.24
Speech x Electrode site	6, 90	.99	= .44	.06
Familiarity x Electrode site	3, 45	.84	= .45	.05
Speech x Familiarity x Electrode Site	6, 90	1.57	= .20	.10
Speech x Hemispheric Specialisation	2, 30	2.42	= .11	.14
Familiarity x Hemispheric Specialisation	1, 15	.51	= .49	.03
Speech x Familiarity x Hemispheric Specialisation	2, 30	.32	= .73	.02
Electrode Site x Hemispheric Specialisation	3, 45	.88	= .38	.06
Speech x Electrode Site x Hemispheric Specialisation	6, 90	.69	= .60	.04
Familiarity x Electrode Site x Hemispheric Specialisation	3, 45	.09	= .92	.01
Speech x Familiarity x Electrode Site x Hemispheric Specialisation	6, 90	1.24	= .30	.08