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Effects of Auditory Processing on Lexical Development in Children with Hearing Impairment

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Effects of Auditory Processing on Lexical Development in Children with Hearing Impairment

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Abstract

Effects of Auditory Processing on Lexical Development in Children with Hearing Impairment

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The purpose of this thesis is to provide a review and discussion of the current literature on auditory processing, speech discrimination, word recognition, and early lexical representations in children with normal hearing and those with hearing impairment in addition to identifying areas in which current research is lacking. This information is needed to consider potential interactions between various factors affecting the development of spoken word recognition. This will also provide a starting point for identifying further research needs. Since children with hearing loss do not receive the same amount of exposure to speech and language as typically developing children, it can be expected that the development of speech and word recognition in this population may progress differently. If we can identify differences in auditory processing and phonological development in children with hearing impairment, we can modify speech and language therapy to focus on more specific and effective targets.

The subsequent chapters will provide a critical review of the current literature on the aforementioned topics. In Chapters 2 and 3, studies assessing differences in processing, attention to sound, intersensory perception, and sound discrimination abilities in children with normal hearing and hearing impairment will be discussed. Chapters 4 and 5 focus on word recognition skills, and early lexical representations. Chapter 6 will synthesize results of available studies and suggest areas in which more research is needed. Together, these chapters will help us gain a better understanding of the complex interactions between auditory processing, executive functioning, phonological development and later word recognition outcomes. By identifying which avenues have the greatest effect on outcomes in cochlear implant users, we can modify speech and language therapy in order to address the unique needs of this special population.

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Chapter 1: Introduction

The purpose of this thesis is to provide a review and discussion of the current literature on auditory processing, speech discrimination, word recognition, and early lexical representations in children with normal hearing and those with hearing impairment in addition to identifying areas in which current research is lacking. This information is needed to consider potential interactions between various factors affecting the development of spoken word recognition. This will also provide a starting point for identifying further research needs. In recent years, the introduction of the cochlear implant has resulted in many deaf children being educated oral/aurally rather than with manual communication. Evidence has suggested that early implantation is a significant predictor of later language outcomes (Houston, Carter, Pisoni, Kirk, & Ying, 2005; Houston & Miyamoto, 2010; Houston, Stewart, Moberly, Hollich, & Miyamoto, 2012; Kirk, Pisoni, & Osberger, 1995; Pisoni, Clearly, Geers, & Tobey, 1999). However, speech and language outcomes in cochlear implant users are highly variable, with some children continuing to lag in development by 2 to 6 years and others developing similarly to children with normal hearing (Briscoe, Bishop, & Norbury, 2001; Kluck, Pisoni, & Kirk, 1997; Pisoni, Clearly, Geers, & Tobey, 1999).

It has been suggested that some of the variation in outcomes in cochlear implant users may be related to how sensory input is processed (Pisoni, Cleary, Geers, & Tobey, 1999). The majority of research on cochlear implant users is focused on a small number of variables such as chronological age, length of deprivation, and age of implantation;

however, considering only these variables leaves much unexplained. Executive functions such as attention to speech (Houston, Pisoni, Kirker, Ying, & Miyamoto, 2003), working memory capacity (Pisoni & Clearly, 2003), and intersensory perception (Gogate, Walker-Andrews, & Bahrick, 2001; Pisoni, Clearly, Geers, & Tobey, 1999) also play a role in speech and language development, as does the ability to discriminate phonemes (Pisoni, Clearly, Geers, & Tobey, 1999).

Auditory processing is one aspect of the development of speech and language skills. It involves not only the perception and representation of an acoustic signal, but also executive functioning processes such as attention and working memory. Processing of auditory information requires an individual to attend to a signal, analyze it, and then interpret the signal as usable information (Jerger, 2007). An understanding of auditory processing may help to illuminate both processes basic to speech perception acquisition and the development of word recognition abilities.

Cochlear implant users are chronologically older than hearing age matched peers and have a more developed cognitive system than typically developing children with similar lengths of hearing experience. Apparent differences in attention to speech may actually be due to assessment tasks being less interesting to more cognitively developed children rather than true differences in sustained attention to speech. Research shows that the brain and nervous system are able to develop even in the absence of auditory stimulation (Pisoni, 2008); however, recent evidence suggests that cortical reorganization takes place during a period of sensory deprivation before cochlear implantation leading to atypical development of speech and language skills (Neville & Bruer, 2001; Rauschecker

& Korte, 1993). It is possible that differences in cortical reorganization following a period of auditory deprivation make it more difficult for cochlear implant users to process and integrate acoustic information. Effortful processing of auditory information leaves less mental resources available for incorporating auditory information into memory (Reed, 2007). If attending to and processing the acoustic signal requires additional processing in cochlear implant users, these children may struggle in more cognitively taxing language related tasks such as word recognition and word learning.

Another key aspect of auditory processing is sound discrimination and the identification of sounds within words. Sound discrimination is the ability to discriminate between differences in sound patterns such as a pure tone versus an alternating tone. Identification of sounds in words includes the ability to phonetically discriminate between speech sounds as well as identify prosody and stress cues. It is important to take into account that sound discrimination and identification of sounds in words are separate processes. Before a child is able to discriminate between sounds in speech, a child must be able to distinguish differences in sounds in general. Studies assessing detection of variation in frequency spectra (Halliday & Bishop, 2005) and temporal ordering abilities (Jutras & Gagne, 1999) have been conducted to determine how well children with hearing impairment are able to discriminate between sounds. Deficits in these areas may be related to the amount of auditory input an individual receives through their device or differences in processing of the acoustic signal.

Infants' perceptual systems are developed as they learn that phonetic differences are used to distinguish between different words. Infants as young as 1 month of age are able to distinguish differences in voicing (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). Between the ages of 10 and 12 infants with normal hearing transition to more language-specific perception of speech and discriminate only consonant and vowel contrasts specific to their native language (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Stager & Werker, 1997; Werker & Tees, 1984). Infants with normal hearing also begin to segment syllables and words from fluent speech and recognize patterns in words at very young ages (Jusczyk & Aslin, 1995; Jusczyk, Cutler, & Redanz, 1993; Jusczyk, Hohne, & Bauman, 1999, Mattys & Jusczyk, 2001; Nazzi, Dilley, & Jusczyk, 2003).

Research on speech discrimination in children with hearing impairment has shown that this ability is not only age dependent, but it also affected by the degree of hearing loss (Boothroyd, 1984; Johnson, Whalley, & Dorman, 1984). As can be expected, the greater the hearing loss, the less able a child is to recognize and discriminate speech patterns. It is possible that cochlear implant users are slower to develop the ability to discriminate speech because of the nature of the acoustic signal they perceive. It is also possible that difference in attention and working memory confound their ability to develop sensitivities to phonetic contrasts. On the other hand, differences in general cognitive development may allow cochlear implant users to develop discrimination abilities more rapidly than children with normal hearing.

Additionally, understanding differences in typical development of speech perception skills will help to determine if speech and language acquisition in cochlear implant users is simply delayed due to factors such as later access to sound or an impoverished acoustic signal or if children follow an atypical trajectory because of factors such as attention to speech and working memory. If a child is unable to distinguish between phonemes, it may affect their ability to acquire skills, such as speech segmentation, affecting later language and literacy skills as well as speech output.

In order to begin recognizing words, infants must form mental representations. It has been hypothesized that infants' early representations of words are more holistic than adult representations and lack fine phonetic detail (Halle & de Boysson-Baries, 1996). Others have posited that infant representations do contain phonetic detail (Jusczyk & Aslin, 1995; Swingley & Aslin, 2000) and their apparent inability to use it in early word representations is actually due to high task demands (Fennell & Waxman, 2010; Werker, Fennell, Corcoran, & Stager, 2002).

Differences in working memory capacity between cochlear implant users and children with typical hearing may be responsible for differences in later speech and language outcomes. Studies on children with normal hearing have shown that the ability to recognize and understand new words may be related to working memory capacity (Gathercole, Hitch, Service, & Martin, 1997; Gupta & MacWhinney, 1997). Additionally, research has shown that development of the lexicon is associated with differences in working memory, such as processing capacity (Gathercole & Baddeley, 1990). It has also been hypothesized that children with normal hearing use sub-vocal rehearsal of phonological information to recall words, which affects working memory capacity (Cowan, Wood, Wood, Keller, Nugent, & Keller, 1998) making it crucial to understand differences in working memory capacity between children with normal hearing and cochlear implant users. If cochlear implant users are slower to develop or have decreased working memory capacity, the processing requirements of novel word learning may be too high. This could lead them to encode words without fine phonetic detail or be unable to map novel words to objects.

Since children with hearing loss do not receive the same amount of exposure to speech and language as typically developing children, it can be expected that the development of speech and word recognition in this population may progress differently. If we can identify differences in auditory processing and phonological development in children with hearing impairment, we can modify speech and language therapy to focus on more specific and effective targets.

The subsequent chapters will provide a critical review of the current literature on the aforementioned topics. In Chapters 2 and 3, studies assessing differences in processing, attention to sound, intersensory perception, and sound discrimination abilities in children with normal hearing and hearing impairment will be discussed. Chapters 4 and 5 focus on word recognition skills, and early lexical representations. Chapter 6 will synthesize results of available studies and suggest areas in which more research is needed.

Chapter 2: Auditory Processing

Auditory processing is described as involving both bottom-up and top-down processing. This means processing is driven by the perceived acoustic signal and the sensory representation of that signal as well as by linguistic knowledge, and world knowledge such as memory and attention (Jerger, 2007). Research on the development of the human auditory system has shown that infants do not form neural projections from the thalamus to the primary auditory cortex until 4.5 months of age (Moore, 2002; Moore & Linthicum, 2007). It is not until this projection forms that the cortical processing of auditory information begins (Houston, 2008). In order to understand how infants learn to discriminate sounds and recognize words, we must first understand how they attend to and process the auditory information that they perceive in their environment. In other words, auditory processing involves paying attention to auditory input, evaluating the acoustical properties of the input (i.e. frequency information and phonetic detail) and integrating that information into the processing system.

The following sections will discuss differences in processing, such as frequency discrimination abilities and temporal structure discrimination, between children with normal hearing and those with hearing impairment. In addition, studies assessing automatic versus effortful processing and studies on attention to sound will be discussed. Automatic processing refers to acoustic information that is processed involuntarily while effortful processing refers to auditory processing which requires additional mental resources such as sustained attention. Studies on attention to sound assess differences between sound versus silent trials present in early development in children with normal hearing and those with cochlear implants.

Sound discrimination abilities and auditory-visual pairing in children with normal hearing and those with cochlear implants will be discussed. The development of sound discrimination for vowels and consonants in children with normal hearing will be reviewed, and categorical and continuous perception of phonemes will be discussed. The ability to pair auditory and visual events will also be discussed as well as the implications these have on the development of further speech and language skills.

DIFFERENCES IN AUDITORY PROCESSING

Even with the use of hearing aids and cochlear implants, children with hearing impairment do not have access to as much of the acoustic signal as children with normal hearing. Auditory input received from a hearing device is not as rich as the natural input received by children with normal hearing (Pisoni, 2008). As a result, auditory processing requires extra effort and uses up more mental resources for children with hearing impairment (Garner, 1974a; Garner, 1974b; Halliday & Bishop, 2005; Jerger, Martin, Pearson, & Dinh,, 1995; Jerger, Grimes, Tran, Chen, & Martin, 1997; Jutras & Gagne, 1999; Rance, McKay, & Grayden, 2004; Simon, Craft, & Webster, 1973). This difference potentially limits the availability of mental resources for allocation to other tasks (Jerger, Damian, Tye-Murray, Dougherty, Mehta, & Spence, 2006; Palmeri, 2003; Reed, 2007). Auditory processing in children with hearing impairment has been studied in two ways: by studying the detection of frequency spectra (Halliday & Bishop, 2005; Rance, McKay, & Grayden, 2004) and by studying temporal structure discrimination capacities (Jutras &

Gagne, 1999). Frequency spectra is typically assessed by testing frequency discrimination and frequency modulation detection. Frequency discrimination studies assess the amount of frequency separation required for listeners to judge two successive tones as different. Frequency modulation detection is assessed by testing the amount of change required for a listener to judge a steady tone and a modulated tone as different (Jerger, 2007).

Detection of frequency spectra was assessed in a study investigating whether children with mild to moderate sensorineural hearing loss were impaired in their ability to discriminate tones of differing frequencies (Halliday & Bishop, 2005). Participants included a group of 22 typically developing children and a group of 22 children with sensorineural hearing loss ranging in age from 6 to 13 years of age. Frequency discrimination was tested at 1 kHz and at 6 kHz by monaural presentation through headphones. Three animated dinosaurs (red, white, and yellow), representing the standard tone, target tone, and a "higher tone", were presented on the computer screen for each trial. Participants had to select the dinosaur (red or yellow) that they believed matched the white dinosaur. There was no time limit given for responses and responses were reinforced by a novel picture or a black cross. To discriminate between tones, children with hearing impairment needed an average of 35 Hz difference at 1 kHz and 387 Hz at 6 kHz, compared to only 21 Hz and 221 Hz at 1 and 6 kHz, respectively, for children with normal hearing. Results indicated that children with mild to moderate sensorineural hearing loss are impaired in their ability to discriminate pure tones of different frequencies. However, there was wide variation in performance among the hearing impaired individuals, including some overlap between the hearing impaired and normal hearing groups. The authors posit that the wide variation in performance may be due to non-auditory factors, such as attention, or that children with reduced auditory sensation may have more difficulty discriminating spectral information.

Frequency discrimination and frequency modulation detection results range from being normal to significantly impaired. It has been shown that frequency modulation detection is related to degree of hearing loss, but frequency discrimination is not affected by degree of loss (Halliday & Bishop, 2005; Rance; McKay, & Grayden, 2004). It is important to note that the lack of association between the degree of hearing loss and frequency discrimination may be affected by the fact that individuals with severe hearing loss were not included in the study on frequency discrimination (Jerger, 2007). Additional research including all ranges of hearing loss needs to be conducted in order to determine if there is in fact an association between frequency discrimination abilities and degree of hearing loss. Studies of temporal ordering abilities have also been used to understand differences in processing. Temporal ordering indicates the ability to discriminate between acoustic stimuli as well as perceive the intervals between those stimuli (Jutras & Gagne, 1999). Performance of children with and without hearing loss on auditory sequential organization tasks was examined by assessing their ability to reproduce sequences of acoustic stimuli varying in type, number, and temporal spacing (Jutras & Gagne, 1999). Participants included forty-eight children divided into four groups: two groups of 6- and 7-year-olds and two groups of 9- and 10-year-olds. Each age group contained twelve children with normal hearing and twelve children with sensorineural hearing loss.

Participants were initially taught associations between two buttons placed in front of them, and verbal (/ba/ and /da/) and nonverbal (pure-tone versus wide band noise) stimuli. In an identification task, children were required to press the correct button following stimulus presentation, in random order. The auditory sequential organization test involved three tasks: reproduction of sequences, in order, with a fixed interstimulus interval (ISI) of 425 ms, reproduction, in order, of sequences of two elements with ISI durations of 30, 150, and 425 ms, and a measure of auditory memory span, presented in sequences of 4, 6, and 8 elements. Interstimulus interval (ISI) refers to the amount of time between stimuli. When ISI durations are short, stimuli are presented at a more rapid rate. Auditory memory span was defined as the sequence with greatest number of elements for which at least 50% accuracy was achieved.

Results indicated significant differences on immediate recall of verbal sequences between children with normal hearing and those with hearing impairment in the 6- and 7-year-old age range. There were no significant differences on nonverbal sequencing tasks or verbal and nonverbal memory span. The 9- and 10-year-olds showed no significant differences on the ability to reproduce sequences containing more than two verbal or nonverbal elements, or for the auditory memory span tasks consisting of verbal stimuli. However, on tasks involving variable ISI duration, children in this age range with hearing impairment had a more difficult time recalling two verbal stimuli (Jutras & Gagne, 1999).

The fact that younger children with hearing impairment had difficulty with verbal tasks, but the older children did not was argued to indicate that verbal memory improves as a function of age in children with normal hearing. Results from these auditory sequential organization tasks indicates that children with hearing impairment have difficulty with temporal ordering when the ISI is variable. However, difficulty with auditory processing cannot be the sole cause since children with hearing impairment were able to correctly identify all of the stimuli when they were presented individually in the identification test. It seems that when timing between stimuli (ISI) varies, children with cochlear implants show difficulty with recall. This may be an indication that auditory processing requires more effort and is done less automatically by children with hearing impairment. If children are allocating a majority of their resources to processing of the auditory stimuli, less mental resources will be available for storage in working memory for later recall.

Children with hearing impairment may be disordered in their ability to detect variations in frequency spectra as well as in temporal structure discrimination and in temporal ordering capacities. None of the studies to date provide much explanation for these differences. Frequency discrimination abilities are possibly affected by the fact that children with hearing loss have less access to these cues caused by reduced auditory sensation. However, the study on temporal ordering hypothesized that there may be additional processes that affect children with hearing impairments ability to process acoustic signals. If this is the case, it is important to figure out what additional processes may impair auditory processing in children with hearing impairment. In the following section, studies involving automatic and effortful processing will be explored to gain a better understanding of the effects of increased auditory demands on auditory processing abilities in children with hearing impairment.

Automatic versus Effortful Processing

Studies have been conducted to assess automatic (information processed involuntarily) versus effortful (requiring sustained attention) auditory processing in children with hearing impairment (Palmeri, 2003). Automatic processing does not require sustained attention or cognitive awareness, like breathing or blinking, while effortful processing does. It has been proposed that individuals have a limited pool of resources for processing which can be allocated depending on the demands of a task. When processing of auditory input is done more automatically, the amount of attention needed for processing is reduced, leaving more processing resources for other things (Reed, 2007). Since the auditory signal is not as rich for children with hearing impairment, even those with cochlear implants, it is important to understand if auditory information processed automatically in individuals with normal hearing is done automatically in those with impairment as well. If children with hearing impairment are less able to process auditory information automatically, they will have to expend more effort (like sustained attention) and use up more mental resources for processing than children with intact hearing. This is of importance because a greater degree of effort in auditory processing might potentially affect an individual's ability to process language. For example, if an individual has to use more processing capacity to attend to speech in competition, they may miss out on important allophonic cues to word recognition.

Two speeded classification methodologies, the Simon task (Simon, Craft, & Webster, 1973) and Garner task (Garner, 1974a; Garner, 1974b), have been used in assessing children with hearing loss. In speeded classification tasks, the variable of interest is the non-target, rather than the target and individuals are required to ignore the non-target and attend only to the target variable (Jerger, Grimes, Tran, Chen, & Martin, 1997). The Simon effect indicates that reaction times are faster when the spatial locations of the stimulus and response button are on the same side of space (Simon, Craft & Webster, 1973). Garner interference (Garner, 1974a; Garner, 1974b), refers to the idea that response times to a target (i.e. talker gender) are slower when a non-target (i.e. spatial location) and a target vary unpredictably than when a non-target is held constant while the target is varied. In other words, Garner interference refers to the idea that the ability to respond to a target is impaired when an additional variable is varied randomly during presentation. Studies involving these two types of tasks will be discussed in the following sections.

Simon Effect

The Simon effect was used in a study involving children aged 5 to 16 with mild, moderate or severe hearing impairment to test children on their orientation response to the spatial location of a stimulus (Jerger, Grimes, Tran, Chen, & Martin, 1997). The participants were required to decide whether a male or a female was saying “Ba Ba”. Stimuli were presented on both the left and right side through a speaker and participants sat at table with a right and left response key in front of them. The participants were instructed to ignore which side the sound was coming from and click the right key for the male voice and the left for the female voice as quickly and accurately as possible. Children with mild to moderate loss had normal Simon interference; but response times were significantly affected by spatial location. This Simon interference; however, was very weak in those individuals with severe hearing loss. These results indicate that individuals with more severe hearing loss do not react overtly to the source of a sound stimulus the way a normal hearing individual does (Jerger, Grimes, Tran, Chen, & Martin, 1997).

Manipulation of a non-target variable influencing response time suggests that the non-target variable was processed automatically despite the listener trying to ignore it. In individuals with normal hearing, both talker gender and spatial location are discriminated automatically, making it difficult to focus on only one variable (Simon, Craft, & Webster, 1973). The fact that children with severe hearing loss were able to focus on one variable and ignore the other indicates that they were effortfully processing the auditory signal. As mentioned before, effortful processing requires more mental resources than automatic processing. If children with severe hearing loss do not process variables in acoustic signals automatically like children with normal hearing, it is possible that they will not have enough mental resources available to attend to and discriminate speech as well as encode and store it in their mental lexicon. This may have significant implications for both word recognition and later lexical development.

Garner Interference

Participants were required to attend to the content of the verbal output (talker gender) and push a button on the corresponding side in the Simon task, whereas in Garner interference, the participants are to ignore the verbal content and respond based on the variation (right versus left) of spatial location. In one study assessing Garner interference, talker gender was the target while the non-target was spatial location (Garner, 1974a). Individuals were unable to ignore the non-target (spatial location) and automatic processing of the spatial location information influenced performance on talker gender identification. There was some Garner interference in children with hearing impairment, indicating that talker-gender and spatial location are processed interactively. However, the degree of interference was abnormally reduced relative to two normal hearing comparison groups matched by chronological age or vocabulary skills. These results indicate that children with hearing impairment have less automatic processing of variability in spatial location (Garner, 1974a; Garner, 1974b).

Two studies assessed Garner interference by looking at response times for nonverbal (spatial location) and verbal targets (“baseball” and “ice cream”) when talker-gender was varied (Jerger, Martin, Pearson, & Dinh, 1995; Jerger et al., 1997). Participants ranged in age from 4 to 16 years old and had an average hearing loss of 70 dB HL. In the nonverbal study (Jerger et al., 1997), the researchers used recordings of male and female talkers saying “Ba Ba” played over loudspeakers on the left and right side of the participant. Participants were instructed to ignore the gender and attend to spatial location: push the right button for the right loudspeaker and the left button for the left loudspeaker. In the verbal study (Jerger et al., 1995) the words “baseball” and “ice cream” were presented from loudspeakers placed directly in front of the participants. Participants were instructed to ignore talker-gender and push the right button for the word “baseball” and the left for “ice cream”.

Performance in both studies was assessed under two conditions: spatial location varied while talker-gender was held constant and both spatial location and talker-gender varied unpredictably. Garner interference was quantified by the difference in performance between these two conditions. Results from both the nonverbal and verbal studies reflected normal Garner interference from talker-gender in children with hearing impairment and this interference was more pronounced in the younger participants. This result suggests that talker-gender was automatically processed causing it to be a distraction, as it would be with normal hearing children in this same task. This also suggests that there is some age related improvement in auditory processing in children with hearing impairment, as is typical for children with normal hearing.

Overall, these results indicate that children with hearing impairment have less automatic processing of variability in spatial location (Garner, 1974a; Garner, 1974b), but that talker-gender is automatically processed (Jerger et al., 1995; 1997). This indicates that children with hearing impairment may require less effort in processing variation in frequency. Although the study by Halliday and Bishop (2005) indicates that children with hearing impairment were less able to discriminate between frequencies than children with normal hearing, fundamental frequencies between male and female voices have a larger difference than the differences used in their study. Results from Garner interference studies (Jerger et al., 1995; 1997) support Halliday and Bishop's (2005) idea that frequency discrimination abilities may be affected by non-auditory factors, such as attention. Further research is needed in order to determine whether ability to process auditory information is based on auditory processing abilities alone or if overall mental capacities are responsible.

ATTENTION TO SPEECH

The development of alert, vigilant, sustained attention occurs between 3 and 18 months of age (Courage & Richards, 2008). Sustained attention can be seen as the ability to direct and focus attention on a specific object or stimuli. Psychologists consider sustained attention a basic requirement for processing information (DeGangi & Porges, 1990). Sustained attention allows an infant to focus processing resources resulting in the ability to actively process information (Courage & Richards, 2008). For example, in order to read and process this sentence, you must be able to focus on the act of reading long enough to get through the entire sentence. In order to process and identify acoustic signals, an individual must be paying enough attention to sound to perceive it as well as to determine changes in the signal. Humans, especially infants, pay more attention to human voices and speech sounds than to other sound stimuli in their environment (Fifer & Moon, 2003; Kisilevsky, Hains, Lee, Xie, Huang, Ye, & Wang, 2003; Newman, 2005). Research measuring heart-rate has shown that neonates prefer their mother's voice in utero (Fifer & Moon, 2003; Kisilevsky, Hains, Lee, Xie, Huang, Ye, & Wang, 2003).

The ability to selectively attend to one voice in the presence of speech competition also develops as infant's age. The abilities of five-month-old infants to separate speech produced by different talkers and to recognize a familiar word in the presence of noise was assessed by presenting infants with repetitions of their own names or unfamiliar names with simultaneous babble in the background has been studied (Newman, 2005). The infants listened to their own names significantly longer when the voice presenting the name was 10dB louder than the background noise. This indicates that by 5 months of age, infants have some ability to selectively attend to one voice in the context of speech competition (Newman, 2005).

The ways in which attention affects the perception of speech was explored using a modification of the high-amplitude sucking technique (Siqueland & DeLucia, 1969) in a study involving 4-day-old and 2-month-old infants (Jusczyk, Bertoncini, Bijeljac-Babic, Kennedy, & Mehler, 1990). The authors first obtained a baseline of high amplitude sucking for each infant. The presentation and intensity of the auditory stimulus was contingent upon the infants' rate of sucking. During baseline, infants were habituated to a randomly varying set of syllables: /bi/, /ba/, and /bu/. Following baseline, focus of attention was manipulated by changing the make-up of a set of syllables to which infants had been habituated. Infants were presented with the familiarized syllables with the addition of a member judged to be a near neighbor (/b^/). Pre- and post-shift sucking rates were recorded and the difference between the two was calculated. Sucking times increased post-shift in both groups of infants indicating that both 4-day-old and 2-month-old infants were able to detect the addition of the new syllable in the set. This shows that even shortly after birth, infants begin paying significant attention to speech.

To date, little research has been conducted comparing children with normal hearing and those with cochlear implants to determine the amount of attention paid to speech during early development (Houston, Pisoni, Kirker, Ying, & Miyamoto, 2003).

Research on this topic is extremely limited. Differences in attention to speech exhibited by infants with normal hearing and cochlear implant users were examined using a modified version of the *Visual Habituation procedure* (Fantz, 1964). In this procedure, infants are habituated to trials of a repeated speech sound presented with a visual display. The same auditory stimuli in addition to novel auditory stimuli are then presented with the same visual display during the trial phase and looking times to the visual display are measured. Increased looking time to the visual display during the presentation of a novel auditory stimulus is taken as an indication that the infant detected the difference in the speech stimuli.

Fourteen pre-lingually deaf infants with profound bilateral hearing loss, implanted before 2 years of age were involved in this study (Houston, Pisoni, Kirker, Ying, & Miyamoto, 2003), including one participant, (CI01), who received a cochlear implant at 6 months of age. Eight of the infants were tested prior to cochlear implantation. Following implantation, seven were tested 1 month post-implantation, eight were tested at approximately 3 months post-implantation, and eight were tested at 6 months post-implantation. The control group included 24 6-month-olds and 24 9-month-olds with normal hearing sensitivity. Children in this group were only tested once.

Two sets of stimulus contrasts were used for habituation: a 4-second continuous “ahh” versus 4-seconds of “hop hop hop” or a 4-second rising vowel /i/ versus 4 second falling vowel /i/. During habituation, infants were presented with a visual display of a checkerboard pattern on a TV monitor paired with one of the sound stimuli (i.e. “hop hop

hop") or no sound at all. Two sound and two silent trials were presented randomly in four blocks of trials. To assess attention to speech, the difference in looking time for sound versus silent trials was recorded for each infant. Results indicated that 6- and 9-month-old infants with normal hearing looked significantly longer during sound trials than during silent trials. There were no differences in attention to sound regardless of age group. Before implantation, cochlear implant users showed no preference for sound over silent trials. After implantation, cochlear implant users attended longer to sound trials, but the difference in looking time was not significant and attention to sound trials was still significantly less than for infants with normal hearing. However, the infant implanted at 6 months of age, CI01, did show a difference in looking times between sound and silent trials that was similar to that of normal hearing infants following implantation. These results suggest that although cochlear implant users' attention to speech increases following implantation, the presence of sound does not sustain the attention of cochlear implant users the way it does in children with normal hearing.

One factor that may have contributed to the differences in looking times between was the difference in chronological age between the two groups of infants. The participants were matched by hearing age, but this does not control for differences in general cognitive development. Matching by chronological age doesn't work well either, since children who have only been hearing for 6 months cannot be expected to perform the same as children who have been hearing for 2 or 3 years. A study that compares cochlear implant users to both hearing and age matched peers would provide some more insight regarding if general cognitive development impacts the attention paid to speech. It is possible that older infants do not show the same kind of preference for sound trials as younger infants, regardless of hearing status. Additionally, the auditory signal perceived through a cochlear implant is not as rich as sound heard through a healthy ear. It is possible that if the signal perceived by cochlear implant users is impoverished, the speech signal may be less interesting to the children. Therefore, we cannot be sure if differences in attention to speech are due to hearing ability and auditory experience or age difference between participants.

Various studies on auditory and visual pairing (Houston, Ying et al., 2003; Miyamoto, Houston, & Bergeson, 2005) use the same age participants, same stimuli, and same procedure as studies assessing infant attention to sound, during the familiarization stage, but do not report results on sustained attention to speech. It has been suggested that if infants are successful in auditory-visual pairing tasks, they must be paying enough attention to speech discriminate sounds, so data specific to how much attention is paid to speech is not collected. Conducting additional studies on attention to speech using different age groups or procedures could give us insight into how early on cochlear implant users begin attending to sound, if general cognitive development has an effect on attention to speech, or if different procedures result in different outcomes. Reduced attention to speech can have severe implications for the development of sound discrimination and word recognition in these infants. Perception and attention to fine phonetic details in speech are known to be important for distinguishing spoken words

(Briscoe, Bishop, & Norbury, 2001; Pisoni, Clearly, Geers, & Tobey, 1999; Pisoni, Svirsky, Kirk, & Miyamoto, 1997). Paying attention to the sequencing of sounds in speech may play a role in learning about the organization of sound patterns in the native language (Houston, Pisoni et al., 2003). Decreased attention to speech may cause children with hearing impairment to be delayed in their development of sensitivities to rhythmic and allophonic cues, which are used in segmenting words from fluent speech (Jusczyk, Cutler, & Redanz, 1993; Jusczyk, Hohne, & Bauman, 1999; Mattys & Jusczyk, 2001; Nazzi, Dilley, & Jusczyk, 2003).

Auditory processing involves not only the perception of the signal, but also the processing of the signal using cognitive processes such as memory and attention. If cochlear implant users' attentional systems are not highly engaged by listening to speech sounds, they might be delayed or require more repetitions in order to learn pairings of speech sounds and objects as compared with children attending to speech sounds and seeking out their significance. Less attention to sound and to changes in sounds may cause processing of acoustic information to be slower. In addition, children with cochlear implants have already experienced periods of auditory deprivation and further lack of attention to sound may cause them to miss out on more exposure during critical periods in development. Earlier implantation and longer duration of cochlear implant use may help develop attention to speech. Attention to speech may also affect infants' ability to associate speech sounds to objects which is an important part of novel word learning.

AUDITORY AND VISUAL PAIRING

It has been proposed that detection of synchronous information across sensory modalities helps guide infants detection of arbitrary relations, which are necessary for word learning (Gogate, Walker-Andrews, & Bahrick, 2001). Studies have been conducted assessing the abilities of children with normal hearing and with hearing impairment to process paired visual and auditory events in order to learn associations. A study assessing word recognition and language comprehension in cochlear implant users revealed that when stimuli were presented with stimuli in a combined auditory and visual condition, they performed better than in either of the isolated conditions (Pisoni, Clearly, Geers, & Tobey, 1999). This study suggests that cochlear implant users do derive some benefit from the combination of auditory and visual information. This makes the results on auditory visual association abilities even more important.

Studies have shown that the ability to make association between visual and auditory events is present as early as 2 months of age in infants with intact sensory systems (Gogate & Bahrick, 1998; Patterson & Werker, 2003; Spelke, 1979), but that this ability does not develop until later in children with hearing impairment (Houston, Ying et al., 2003; Miyamoto et al., 2005). The ability to learn arbitrary relationships between visual events, speech sounds, and objects was not evidenced until approximately 12 to 14 months in cochlear implant users (Werker, Cohen, Lloyd, Casasola, & Stager, 1998; Houston, Ying et al. 2003; Miyamoto et al., 2005). Though pairing auditory and visual events is not necessarily crucial for success in language development, evidence has shown that the ability to make associations between auditory and visual events does improve across development in children with normal hearing (Miyamoto et al., 2005).

Infants as young as 2 months old are able to perceive correspondences between acoustic-phonetic information and visual articulatory information (Patterson & Werker, 2003). In one particular study, infants were presented with a vowel along with two videos. In one, the person was articulating the vowel being presented, while in the other a different vowel was being articulated. Infants looked longer and more often to the video that corresponded to the vowel they were hearing than to the incorrect vowel production.

The ability of young infants to perceive temporal synchrony in bimodally specified events involving an auditory and visual stimulus has also been studied. In one study, 4-month-old infants were presented with a repeating sound, paired with a video of an object bouncing in temporal synchrony with the repeating sound, and one with an object bouncing out of sync with the sound (Spelke, 1979). Results indicate that infants displayed more first looks to the object bouncing in synchrony with the auditory stimuli. This suggests that even at such a young age, infants are able to perceive bimodal correspondence.

In order to assess the effects of temporal synchrony on the ability to associate labels with objects, a group of 7-month-old infants was tested using a habituation Switch task (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). In this method infants are presented with two word (or syllable)-object pairings (i.e. word A pairs with object A, word B pairs with object B). During testing, the "switch" trial presents one of the familiar words with the opposite object (i.e. word A is presented with object B). If infants have not formed the association between the word and the object, the looking time to same and switch trials should not be significantly different.

The 7-month-old infants were presented with two video films of a vowel (/a/ or /i/) paired with a separate object (a porcupine and a crab or a star and a lamb chop). Objects were presented under three conditions: moving either in-sync or out of sync with the auditory stimulus or not moving at all. Following habituation, infants were tested in all the three conditions in a series of four trials per condition: two no change trials (controls) and two in which the vowel-object pairings were switched (i.e. the /a/ was paired with a porcupine and the /i/ with the crab during habituation, but were presented vice-versa during testing). Infants' looking time to change versus control trials was recorded. Infants attended longer to switch trials than control trials when the visual presentation was in temporal synchrony with the vowel stimulus. Under the other two conditions (out-of-sync and stationary); however, the infants failed to demonstrate vowel-object association and did not attend longer to the switch trials. This indicates that at young ages, the use of temporal synchrony facilitates sound-object associations (Gogate & Bahrick, 1998).

Twenty-one infants with prelingual, profound, bilateral hearing loss, implanted before the age of 2 were assessed on their ability to associate speech patterns with visual events (Houston, Ying et al., 2003) using a split-screen version of the *Preferential Looking Paradigm* (Hollich, Hirsh-Pasek, Golinkoff, Brand, Brown, Chung, Hennon, Rocroi, & Bloom, 2000). In a traditional *Preferential Looking Paradigm* (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987), infants are familiarized with two pairings of a novel word and a novel object, one at a time. In the split-screen version of this paradigm, the two videos are presented simultaneously on a split-screen display, one on the right and one on the left, during habituation. During testing, both objects are presented, but only one of the words is presented. Infants' eye movements while watching the presentations on the screen are recorded. Average looking times for target and non-target are calculated and the difference in looking times is used to determine the ability to learn the association between speech sounds.

To examine variability based on age of implantation, cochlear implant users were divided into two groups: earlier implanted (implants activated between 7 and 15 months) and later implanted (implants activated between 16 and 25 months). The cochlear implant users were compared to four age-based control groups with normal hearing: 25 6-month-olds, 26 9-month-olds, 24 18-month-olds, and 12 30-month-olds. Stimulus items were identical to the ones in the previously mentioned study by Houston, Pisoni and colleagues (2003) and contained a change in intonation (4 second rising intonation of vowel /i/ versus 4 second falling intonation of vowel /i/) or varied in continuity (a 4 second vowel continuous /a/ versus 4 seconds of discontinuous "hop hop hop"). Each of the stimulus items was paired with a temporally synchronous visual display. The continuous /a/ was paired with a toy airplane moving from left to right and "hop hop hop" was paired with a toy kangaroo bouncing up and down. The falling /i/ was paired with a ball rolling down a ramp and the rising /i/ was paired with a bubble rising inside a lava lamp. The authors posit that infants would not be able to associate speech sounds with visual events if they were unable to discriminate between the speech sounds.

Infants were first shown the two videos on the split-screen display without any auditory input. The infants were then shown the videos individually and taught to associate them with a one of the speech patterns. During testing, both videos were presented simultaneously on the split-screen, as during habituation, and one of the speech sounds was played. Average looking times for target and non-target were calculated for each infant and the difference in looking times was used to determine the ability to learn the association between speech sounds. Results indicate that differences in looking time to target versus non-target were significantly greater than 0 in the children with normal hearing (.2 seconds) and the earlier implanted group (.21 seconds). The differences in looking time to target versus non-target were not significantly greater than 0 for the group of later implanted cochlear implant users. These findings reveal that the differences in looking time between earlier implanted cochlear implant users and children with normal hearing are almost identical. Earlier implanted infants demonstrate the ability to learn associations between speech sounds and objects while infants implanted at later ages have more difficulty learning associations suggesting that early implantation may help facilitate the use of intersensory perception in learning associations between sounds and objects (Houston, Ying et al., 2003; Houston, 2008).

These finding on cochlear implant users' ability to learn associations between temporally synchronized speech sounds and objects were replicated (Miyamoto et al.,

2005) using a split-screen version of the *Preferential Looking Paradigm* (Hollich, Hirsh-Pasek, Golinkoff, Brand, Brown, Chung, Hennon, Rocroi, & Bloom, 2000). The speech sounds used in the discrimination portion of the study (“ahh” and repetitions of “hop”) were paired with a changing visual event and presented to the same groups of infants. Similarly to the study by Houston, Ying, and colleagues (2003), the “ahh” was paired with a plane moving across the screen and the repetitions of “hop” were paired with a bouncing kangaroo. Results showed that infants implanted prior to 12 months looked significantly longer to the corresponding video than the non-target while infants implanted after 12 months of age did not. The results from infants with cochlear implants were compared to data on children with normal hearing. Children with normal hearing’s preference for the target video increased with age, suggesting that the ability to make auditory and visual associations improves over time. These findings reveal that children implanted at an earlier age perform better, relative to their age, than children implanted later on indicating that earlier implantation may facilitate a developmental speech and language trajectory that is similar to that of children with normal hearing.

Additionally, the results are indicators that the ability to make auditory and visual associations, an ability thought to predetermine later word learning skills (Gogate, Walker-Andrews, & Bahrick, 2001), is delayed in cochlear implant users in comparison to children with normal hearing. These results by no means suggest that the ability to pair auditory and visual events is necessary for language or phonological acquisition. The ability to associate speech sounds with visual events does, however, reflect the ability to discriminate between speech sounds (Houston, Ying et al., 2003). If infants were unable to discriminate between the sounds presented, they would be unable to pair differing sounds with differing visual events. If the ability to learn arbitrary associations between auditory and visual stimuli really is a precursor to later word learning, these results could have significant implications for children implanted with cochlear implants.

DISCUSSION AND CONCLUSIONS

Overall, studies assessing auditory processing and speech discrimination in children with normal hearing and those with hearing impairment reveal significant differences. Children with hearing impairment are not as accurate at detecting and processing various aspects of the acoustic signal as well as having more difficulty sequencing auditory stimuli when ISI varies (Halliday & Bishop, 2005; Jutras & Gagne, 1999; Rance, McKay, & Grayden, 2004). Children with hearing impairment may require more mental capacities for processing information in the acoustic signal (Garner, 1974a; Garner, 1974b; Jerger et al., 1995; Jerger et al., 1997; Simon, Craft, & Webster, 1973). It has been suggested that differences in sequencing auditory stimuli may be a reflection of additional abilities, such as working memory as well as auditory processing abilities (Jutras & Gagne, 1999). This result suggests that the processing of stimuli may not be affected by their sensitivity to the signal alone, but that the way in which they process it may differ from that of children with normal hearing. This may be an indication that auditory processing requires more effort and is done less automatically by children with hearing impairment. If children are allocating a majority of their resources to processing the auditory stimuli, less mental resources will be available for differentiation of phonemes from the acoustic signal and encoding and storage in working memory for later recall (Jerger, 2007). This may have significant implications for both word recognition and later lexical development since learning words requires a listener to be able to distinguish between speech sounds and attend to cues, such as allophonic variation, for segmenting fluent speech. The fact that verbal memory improves with age is an indication that though children with hearing impairment may not perform as well as children with normal hearing at early ages, they do make gains and have similar outcomes in verbal memory at later ages. This is of importance because if some of the processing difficulties experienced by children with hearing impairment are a result of other executive functioning differences, improvement in these areas over time may allow children with hearing impairment to process auditory information in a more automatic manner. If this is the case, it may be that with increased device use, cochlear implant users will require less mental resources to process differences in the acoustic signal leaving more mental resources available for them to attend to tasks with higher demands such as word learning.

Studies on older infants suggest even following implantation, the presence of sound does not sustain the attention of cochlear implant users the way it does in children with normal hearing (Houston, Pisoni et al., 2003). This decreased attention can have severe implications for the development of sound discrimination and word recognition in these infants because auditory processing involves not only perceiving the signal, but processing the information contained in the signal. If sustained attention is a necessity for processing sensory input (DeGangi & Porges, 1990), decreased attention to sound patterns may increase the time needed for processing auditory stimuli or inadequate processing of the signal. Perhaps children with normal hearing are able to process auditory input more automatically because they are able to focus their attention on the speech signal. If cochlear implant users require more effort in processing on auditory stimuli, increased ability to focus attention on speech may help develop the ability to process acoustic signals more automatically. If children with hearing impairment are already allocating more mental resources to processing acoustic information it may take them longer to process a stimulus. This could lead cochlear implant users to miss out on early language experiences in their environment. The fact that implantation at an earlier age may help develop attention to sound and that earlier implanted infants may reach the same levels as children with normal hearing is of great importance. If this is the case, earlier implantation may allow a cochlear implant users attention to speech to develop more rapidly resulting in less of a developmental lag when compared to children with normal hearing. Attention to speech may also affect infants' ability to associate speech sounds to objects which is an important part of novel word learning (Houston, Pisoni, et al., 2003).

Although auditory and visual pairing is not a prerequisite for word learning, it has been hypothesized to be a predictor of later word learning abilities (Gogate, et al., 2001). Results from auditory and visual pairing studies indicate that intersensory association may be affected by when an infant has access to both sensory systems (Miyamoto et al., 2005). Infants later implanted may have been unable to learn pairing between auditory and visual events for two reasons: they did not detect the intersensory redundancy or they detected the intersensory redundancy, but were unable to encode it due to insufficient training (Miyamoto et al., 2005). The first possibility would reflect cortical reorganization from a longer period of auditory deprivation (Neville & Bruer, 2001; Rauschecker & Korte, 1993; Pisoni, 2005) or impairment of neural pathways between the auditory cortex and other sensory cortices (Kral, Hartmann, Tillein, Held, & Klinke, 2000; Ponton & Eggermont, 2001). The second possibility would reflect difficulty with general processing abilities (Jutras & Gagne, 1999). This may be linked to infants' abilities to attend to auditory information and the need to process such information effortfully. If this is the case, infants may not have had enough mental resources available to pair the auditory stimuli to the corresponding visual since they were using the majority of their resources to perceive the auditory stimulus alone. It is possible that early implantation may help facilitate the use of intersensory perception in learning (Miyamoto et al., 2005). When earlier implanted children are compared to children with normal hearing, it is evident that the ability to pair auditory and visual stimuli increases with age in both groups. This suggests that with increased sensory experience, infants begin to develop the ability to integrate information from various senses and use this information for learning.

Taken together, these results indicate that children with normal hearing and those with hearing impairment differ in their proficiency to process and attend to auditory information as well as incorporate this information into their systems. As mentioned before, it may be due to the differences in neural organization (Neville & Bruer, 2001; Rauschecker & Korte, 1993; Kral, Hartmann, Tillein, Held, & Klinke, 2000; Ponton & Eggermont, 2001), access to the acoustic signal (Houston, Ying, et al., 2003), availability of mental resources (Jerger, 2007), or additional executive functioning abilities such as attention and memory (Jutras & Gagne, 1999). Additional research is needed to determine exactly what causes these differences in processing ability in order to develop adequate intervention approaches. Regardless of what causes these differences, they are present and may have severe implications for later speech and language abilities.

Before moving on to word recognition we will take a look at how infants develop the ability to discriminate speech sounds. Recognizing spoken words involves identifying sequences of segments and features from acoustic-phonetic properties in the speech signal (Boothroyd, 1970, 1997; Eisenberg, 2007). Differences in speech sound discrimination may impact the ability to segment and recognize words in fluent speech. In Chapter 3 we will discuss how auditory processing capacities demonstrated in Chapter 2 are at work when infants are using these abilities to discriminate between speech sounds they hear, before semantic meaning is involved.

Chapter 3: Speech Sound Discrimination

Learning words requires knowledge of the sound form as well as semantic and syntactic properties of the word. Infants younger than 12 months of age may "know" very few words, but may still be able to learn the sound form of words without attributing meaning to the word, allowing them to recognize words (Swingley, 2009). Before children can learn to recognize words, they must learn to identify sounds heard in speech. The amount of phonological information that needs to be stored in the mental lexicon in order to perceive and produce words is at least the minimal amount of information needed in order to distinguish words from each other (Houston, Ying et al., 2003; Stager & Werker, 1997; Swingley, 2009). Early in development, infants are exposed to many different sets of sound contrasts through the speech they hear around them. In order to acquire the relevant sound contrasts of their native language, infants must interpret and store segmental information from continuous speech, which contains an enormous amount of variable phonetic information (MacKain, 1982). Sensitivity to language-specific properties is important for segmenting words from fluent speech which may cause reduced word recognition abilities. Infants must learn to recognize which phonemes and allophones are relevant to their own language. This knowledge can be used for detecting word boundaries within fluent speech. Infants must have some idea of where a word starts and where it ends if they are to learn that a speech sound sequence is an individual word. Evidence demonstrating the use of various perceptual features in word segmentation will be discussed in a later section.

The following section discusses the ways in which children with normal hearing learn to discriminate consonant and vowel contrasts in speech. It has been shown that children with normal hearing use both categorical and continuous perception when discriminating between sounds. A further explanation of these concepts as well as studies providing evidence for this notion will be introduced. After the discussion of typical development, the existing studies on sound discrimination abilities in cochlear implant users will be discussed. To date, the research in this area is very limited. Continued research in this area is critical because of the implications that sound discrimination abilities may have on the development of later speech and language abilities.

Typical Development

Infants are born with general auditory processing skills that are modified selectively by experience and activities in the language-learning environment (Aslin & Pisoni, 1980). One of infants' earliest acquired abilities in the development of speech perception is learning the sound system of their native language. The sound system of a language is defined by phonetic contrasts used to denote meaning between words in the language. Infants are able to learn the sound patterns of their native language before learning actual words (Yeung & Werker, 2009).

Best's Perceptual Assimilation Model (Best, 1994; Best, McRoberts, & Sithole, 1988) suggests that listeners categorize novel speech events by their similarity to native categories, or to "prototypes". This model predicts that only infants who have yet to form native phonological categories will be able to discriminate non-native sounds. Various studies have indicated that 4- to 6-month-old infants discriminate the phonetic differences that differentiate phonemes in both their native and non-native languages (Jusczyk, 1995; Kuhl, 1987;Werker, 1995). These findings are of importance because they indicate that in the first months of life, infants are in the process of identifying phonetic details which are important in their ambient language. These native language distinctions are necessary for infants to begin fine tuning their perceptual skills to be more language-specific.

At approximately 10 to 12 months of age, children shift from perceiving all phonetic distinctions of the world's languages to perceiving consonant and vowel contrasts that are meaningful in their ambient language (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Stager & Werker, 1997; Werker & Tees, 1984). This shift reflects reorganization of infants' perceptual sensitivities during this time period resulting in formation of phonological categories specific to the ambient language. This decrease in sensitivity to nonnative speech contrasts reflects a shift from language-general to language-specific speech perception skills, caused by early exposure to language in the environment. Knowledge of organization and properties of speech sounds and speech patterns in the native language helps infants learn to segment fluent speech into individual words providing the fundamentals for word recognition and learning. Without this ability, infants may be hindered or delayed in word recognition and other language skills.

In addition to learning to perceive which contrasts are relative to the native language, infants begin to develop perceptual sensitivities to contrasts that help them organize relevant phonemes into categories. The classic study conducted by Eimas, Siqueland, Jusczyk and Vigorito (1971) evidenced that by 1 month of age, babies are able to distinguish differences in voicing (i.e. /pa/ versus /ba/) using a modification of the reinforcement procedure (Siqueland & DeLucia, 1969). The authors first obtained a baseline of high amplitude sucking for each infant. The presentation and intensity of the auditory stimulus was contingent upon the infants' rate of sucking. Following baseline, variations of /p/ and /b/ were presented in three conditions. In the first condition, VOT differed by 20msec (+20 and +40msec) and the two stimuli were from different adult phonemic categories. In the second condition, VOT again differed by 20msec (-20 and 0msec or +60 and +80msec), but the two stimuli were from same phonemic category. The third condition was a control condition. Discrimination ability was measured by an increase in response rate to a second speech sound after habituation to the first speech sound. Results from the study indicate that recovery from habituation was greater when the two stimuli were from different adult phonemic categories indicating categorical perception. In categorical perception, discrimination of the sounds is significantly easier across the adult phonemic boundary than within the adult phonemic category (Boersma & Chládková, 2013). This indicates that 1-month-old infants not only respond to speech sounds and can make fine discriminations, but can also perceive speech sounds along the voicing continuum categorically, even with limited exposure and no experience producing the sounds. This implies that categorical perception of speech (perception in a linguistic mode) may well be part of the biological makeup of humans (Eimas et al., 1971; Eisenberg, 2007).

Studies assessing vowel discrimination have shown that infants generalize variations of a vowel to a "prototype" of that vowel and categorize vowels based on their similarity to that prototype; referred to as the "perceptual magnet effect" (Grieser & Kuhl, 1989). In a study involving English-learning 6-month-olds, the hypothesis that infants organize speech categories around "prototypes" was tested (Grieser & Kuhl, 1989). Infants were first introduced to "good" exemplars from two different vowel categories. Following this, 32 novel exemplars for each vowel category, varying in the degree to which they conformed to adult-defined prototypes, were presented to the infants. Infants were able to sort the novel stimuli into the correct vowel category over 90% of the time. Two additional groups of infants were trained on either a prototypical or non-prototypical exemplar from a vowel category. The groups were tested using 16 novel variants from the vowel category. Infants that were originally presented with the prototypical version were significantly better at generalizing to the novel presentations than the infants that had been presented with the non-prototypical version. These results showed that infants generalize variation of the English vowel /i/ to a prototypical version rather than an atypical version, evidencing the perceptual magnet effect (Grieser & Kuhl, 1989). Perception of vowels may be influenced by a combination of both innate perceptual biases and experienced distribution of vowel input. This further supports the hypothesis that input and linguistic relevance affect infants' perception of consonants and vowel (Houston, 2008).

The perceptual magnet effect has been explored in adults as well as in infants (Kuhl, 1991). Adults rated the "goodness" of 64 exemplars of the vowel /i/ on a scale of 1 to 7. Ratings showed that the further the variant was from the prototypical production of /i/, the lower it was rated. This indicates that vowel categories have a vowel space location that is considered “best”, or prototypical. The adults, as well as a group of 6-month-olds, were then presented with the prototypical or non-prototypical version of /i/ and required to generalize other variants from the same vowel category. Results indicated that adults that had heard the prototypical version of /i/ were significantly more successful at generalizing to other /i/ variants. Infants also showed greater generalization of the variants of /i/ when the prototypical version of the vowel was introduced. Interestingly, their generalization responses were highly correlated with those of the adults, further indicating that both adults and infants categorize and discriminate vowels in a similar manner.

This research indicates that young infants are sensitive to small differences in suprasegmental features of consonants (i.e. VOT) and variable productions of the same vowels. Infants also have the ability to group phonemes into categories based on the similarity to a “prototype” (Kuhl, 1991). As mentioned previously, the ability to detect minor differences in phonemes is critical for discriminating phonetic contrasts in connected speech, which is what children are exposed to early on in life. Knowledge of organization and properties of speech sounds and speech patterns in the native language helps infants learn to segment fluent speech into individual words, providing the fundamentals for word recognition and learning. Additionally, sensitivity to variations in acoustic signals of speech sounds can be stored as phonological information in the lexicon in order to distinguish different words from each other, but group variable productions of the same word together. Without this ability, infants may be hindered or delayed in word recognition and other language skills.

Children with Hearing Impairment

There are very few studies that assess sound discrimination abilities in cochlear implant users. Unlike the studies on children with normal hearing, research on discrimination abilities in cochlear implant users focuses more on gross-level distinctions rather than ability to discriminate fine phonetic details. This may be in part due to the fact that behavioral responses to auditory stimuli may be inconsistent, making it difficult to precisely determine the perceptual acuity of these infants (Houston, Ying et al., 2003). It is important to also consider that the input received from the device may vary between infants (Houston, Ying, et al., 2003). This means that differences between infants or groups of infants may not only be a result of developmental growth from access to auditory information, but may be also be affected by differences in quality of the input received.

Following assessment of cochlear implant users' attention to speech, speech discrimination ability of infants with normal hearing and cochlear implant users was assessed using the same stimulus items (Houston, Pisoni et al., 2003). Stimulus items contained a change in intonation (4 second rising intonation of vowel /i/ versus 4 second falling intonation of vowel /i/) or varied in continuity (a 4 second vowel continuous /a/ versus 4 seconds of discontinuous “hop hop hop”). Infants were habituated to one of the stimulus items from one of the pairs. Following habituation, infants were tested on two types of trials: an “old trial” in which the familiarized speech sound was presented (i.e. “hop hop hop”), and a “novel trial” in which a new speech sound (i.e. “ahh”) was presented. To assess discrimination abilities, the difference in looking time towards novel versus old trials was calculated for each infant. Children with normal hearing looked significantly longer to novel than old sound trials; prior to implantation, cochlear implant users did not. Following implantation, differences between the typically developing group and the cochlear implant users did not approach statistical significance suggesting that after implantation, cochlear implant users improve in their ability to discriminate speech patterns. Overall, there was also a larger difference in discrimination ability for the continuity contrast (“ahh” versus “hop hop hop”) than for intonation contrast (rising versus falling /i/). These results suggest that children with normal hearing and cochlear implant users are able to discriminate gross-level contrasts to similar degree and that cochlear implant users’ discrimination of speech patterns improves with access to sound in the first few months following implantation.

In a similar study, 26 infants with congenital profound hearing loss were assessed using a *Visual Habituation procedure* (Fantz, 1964). Of the 26 infants, eight received an implant before 12 months and seventeen received one between 12 and 24 months of age. Infants were tested at several intervals following cochlear implantation. These intervals were separated into three interval groups: 1 day, 1 week, and1 month after implantation (interval group 1), 2 months, 3 months, and 6 months after implantation (interval group 2), and 9 months, 12 months, and 18 months after implantation (interval group 3).

Stimulus items included a continuous “ahh” versus eight repetitions of “hop” and were presented with a visual display of a red and white checkerboard pattern. Results reveal that infants implanted prior to 12 months and those implanted after 12 months both showed longer looking times to the novel versus old trials (Miyamoto et al., 2005). This indicates that after cochlear implantation, infants are able to discriminate between continuous and discontinuous sound patterns. This may mean that shortly after implantation, cochlear implant users begin developing the ability to process speech patterns. This also means that even after longer periods of auditory deprivation, infants still learn to process gross-level differences in speech patterns.

Though the results of Houston, Pisoni and colleagues (2003) indicate that cochlear implant users are able to discriminate gross-level differences (continuity and intonation) in speech, very little is known about the ability of young cochlear implant users to perceive fine phonetic detail and discriminate between speech sounds. The ability to process voicing cues in stop consonants was assessed in a group of children aged 11 to 14 with mild, moderate, or severe hearing loss (Johnson, Whalley, & Dorman, 1984). Listeners were presented with stimuli from along VOT continua for English stop consonants. Children with mild to moderate hearing loss had difficulty identifying place of articulation. The authors posit that temporal cues to voicing are processed normally even in the presence of abnormal processing of spectral cues to place of articulation. In contrast to mild and moderate impairment, those with severe hearing impairment did not process cues for voicing normally and did not show evidence of categorical perception for change in place of articulation. As discussed in the previous section, studies have shown that children with normal hearing do have the ability to discriminate consonants in a categorical manner.

One hundred twenty students with prelingually acquired sensorineural hearing loss, ranging in age from 11- to 18-years old, were assessed on perception of speech pattern contrasts using a forced-choice procedure (Boothroyd, 1984). Four contrasts were evaluated: number of syllables per phrase, vowel nucleus, voicing and continuity of consonants, and place of articulation. Contrasts were placed in word-initial or word-final positions of a monosyllabic words embedded at the end of a short carrier phrase. Subjects heard each test stimulus twice and were then asked to write the words heard in a in a list of 10, monosyllabic, consonant-vowel-consonant words containing some of the stimulus items. Open-set recognition performance was measured as a percentage of phonemes recognized (phonemic scoring). Phonemic scoring was used rather than word scoring because subjects unable to recognize words can sometimes still recognize individual phonemes within the words (Boothroyd, 1968).

To examine speech perception measures as functions of degree of hearing loss, subjects were divided into five unequal groups on the basis average thresholds: 55-74 dB HL, 75-89 dB HL, 90-104 dB HL, 105-114 dB HL, and 115-124 dB HL. The general pattern of relationships between contrast perception and degree of hearing loss showed that performance decreased with increasing hearing loss. Decreases in performance between suprasegmental contrasts and consonant place contrasts, and the relative difficulty of the contrasts were constant across all five hearing loss groups, indicating they were not correlated to degree of hearing loss.

In a second experiment, eighteen students 14 to 19 years of age, with pure tone averages ranging from 75 to 114 dB HL were assessed. A forced-choice procedure was used to measure the perception of speech pattern contrasts. The binary features evaluated were: talker gender, intonation, vowel height, vowel place, voicing of word-initial consonants, and continuance of word-initial consonants. This time, each subtest incorporated two binary features (i.e. responding "ban" for pan was incorrect for voicing, but correct for continuance). For the four segmental features, contrasts were placed in word-initial or word-final positions of a monosyllabic word embedded at the end of a short carrier phrase. The pitch related contrasts were presented in short phrases. Response alternatives were a male and female “happy” face (natural intonation) and a male and female “sad” face (monotone).

Subjects were again divided into three frequency average thresholds: 75-89 dB HL, 90-104 dB HL, and 105-114 dB HL. Results indicate that consonant voicing and consonant continuance scores were significantly correlated with degree of hearing loss. Neither contrast appeared to be perceptible to subjects with 105-114 dB HL. Subjects in the 75-89 and 90-104 dB HL groups were able to easily identify gender of the speaker, while the subjects in the 105-114 dB HL group could not do so. All subjects performed only at the chance level for the intonation contrast. The combined contrast score was significantly related to phoneme recognition score. This suggests that the inability to detect consonant contrasts will affect an individual's ability to recognize phonemes in words.

Using a novel version of the *Visual Habituation procedure* (Houston, Pisoni et al., 2003) three groups of infants were tested on their abilities to discriminate speech sounds based on non-words. The three groups of infants included a group of deaf infants tested prior to implantation, cochlear implant users post-implantation, and a group of age-matched normal hearing children (Horn, Houston, & Miyamoto, 2007). Infants sat on their caregivers' laps in front of a TV monitor. Visual stimuli were displayed in the center of the TV monitor, at approximately eye level to the infants, while auditory stimuli were presented through the left and right loudspeakers of the TV monitor. Stimuli included five examples of two highly contrastive naturally produced audiovisual non-words: boodup and seepug. During the habituation phase, infants were presented with four examples of seepug or boodup. The test phase consisted of 10 alternating trials (A) and 4 non-alternating trials (NA). For the A trials, a new example of the two non-words seepug and boodup were presented in alternating order. For the NA trials, two examples of a habituated non-word were presented in alternating order. Using two examples of a non-word in the NA trail ensured that differences in looking time during the A trials was not due to indexical variation.

Results indicate that children with normal hearing and cochlear implant users both discriminated the two non-words. Prior to implantation, cochlear implant users could not discriminate between the two words. These results indicate that within three months of cochlear implant use, infants can discriminate speech sounds. Using different examples of the habituated non-words provides evidence that infants can discriminate speech sounds based on spectral differences rather than just indexical properties.

Speech feature discrimination abilities for consonants and vowels in “stars” and “low performers” was analyzed over a period of 6 years of implant use using the *Minimal Pairs Test* (Robbins, Renshaw, Miyamoto, Osberger, & Pope, 1988). The *Minimal Pairs Test* is a word recognition test developed specifically to assess speech perception in children with cochlear implants or hearing aids. The test is made up of 20 English minimal pairs of consonant-vowel and consonant-vowel-consonant words whose initial consonant or vowel differ only in one feature, consonant voicing, place, or manner, or vowel height or backness (i.e. “fan” versus “van” or “boot” versus “beet”). Children are presented with two side-by-side line drawings: one of the target word and one of a foil. Upon presentation of the word, they are required to point the picture corresponding to the word they hear. Classification as “stars” or “low performers” was based on performance on the *Phonetically Balanced Kindergarten* word lists (PB-K) (Haskins, 1949); an open-set test used to measure word recognition and lexical selection processes. “Stars” are defined as children who did exceptionally well on the after two years of cochlear implant use. “Low performers” are defined as cochlear implant users that scored in the bottom 20% of the PB-K after two years of implant use (Pisoni, Svirsky, Kirk, & Miyamoto, 1997).

Findings revealed that “stars” consistently outperformed the “low performers” group across all three consonant features: place, manner, and voice. Discrimination performance did improve over time for both “stars” and “low performers” and both groups had trouble perceiving, encoding, and discriminating fine phonetic detail. Following one year of implant use, “stars” were able to discriminate manner of articulation (i.e. stop versus fricative) and showed consistent improvement in discriminating manner and voicing contrasts. However, even after five years of cochlear implant use, “stars” still had difficulty differentiating place of articulation. Following four years of implant use, “low performers” still had trouble discriminating differences in manner of articulation and struggled with voicing and place of articulation discrimination after five to six years of implant use (Pisoni, Clearly, Geers, & Tobey, 1999). A longitudinal study directly comparing cochlear implant users to hearing-age matched peers would allow us to further determine how impaired cochlear implant users are in speech feature discrimination.

These results indicate that both “stars” and “low performers” encode using “coarse” phonological representation—representations that are “underspecified” and contain less fine-grained acoustic-phonetic detail than those used by typically developing children. It is likely that if a child cannot discriminate small phonetic differences they will struggle to recognize words in isolation without contextual cues. They may also have difficulties retrieving phonological representations from memory and recognizing and imitating non-words. Overall, these findings suggest that there may be differences between children with normal hearing and cochlear implant users in their processes of encoding sensory information and the phonological representations that are used for subsequent word learning and lexical development (Pisoni et al., 1999). Knowledge on which properties from the auditory signal children with hearing impairment have access to early on and encode in lexical representations is an important area for future research. This may give us some indication of how early word representations are stored in cochlear implant users' lexicons. Differences in the amount of detail encoded in these early representations may cause impairments in phonological discrimination, which could have consequences for lexical development such as receptive vocabulary (Briscoe, Bishop, & Norbury, 2001). More reliable measures of cochlear implant users discrimination abilities and data on cochlear implant users' abilities to discriminate fine phonetic distinctions is crucial to our understanding of development of speech and language in hearing impaired users, specifically because sensitivity to differences between similar contrasts are necessary for accurate perception of speech.

DISCUSSION AND CONCLUSIONS

Sound discrimination studies reveal that infants with normal hearing discriminate sounds in a similar manner to adults (Eimas et al., 1971; Kuhl, 1991). This suggests that infants with normal hearing recognize variation in suprasegmental aspects (i.e. frequency, intensity, VOT) of phonemes. Early studies on children with hearing impairment indicate that the greater the hearing loss, the less able the individual is to perceive contrasts (Boothroyd, 1984). Children with severe hearing loss are unable to process temporal cues to voicing (VOT) and perceive differences in consonant place. Even children with mild to moderate loss that are sensitive to voicing cues have difficulty processing spectral cues related to place of articulation (Johnson et al., 1984). The fact that perception of contrasts and ability to recognize phonemes is correlated suggests that if cochlear implant users are unable to detect differences in consonants and vowels, they will be unable to identify the phonemes within individual words. This may have severe implications for later word recognition abilities because of high phonetic similarity between words in the language. If cochlear implant users are presented with phonetically similar words and are unable to detect differences between them, they may incorrectly code and store representations in their mental lexicon.

Research on sound discrimination of very young cochlear implant users focuses mainly on gross-level differences rather than specific differences in temporal and spectral cues in phoneme identification. However, research provides evidence that infants with cochlear implants are able to discriminate sounds in terms of continuity and intonation changes (Houston, Pisoni et al., 2003; Houston, Ying, et al., 2003; Miyamoto et al., 2005). Additional research focusing on the ability to discriminate phonetic detail is needed to fully understand the development of speech discrimination in cochlear implant users. Given that very little is known to date about the specific speech contrasts cochlear implant users may be able to detect early on, it is difficult to determine which sound categories to focus on for therapy. Based on the studies indicating decreased discrimination of frequency and temporal cues necessary for determine voicing and place of articulation in hearing impaired children, it can be inferred that cochlear implant users will have difficulty distinguishing sound contrasts that fall within the same category (i.e. /p/ and /b/). Investigating speech discrimination abilities of cochlear implant users for smaller acoustic differences, like minimal pairs, would provide more thorough knowledge on the sensitivity and ability to distinguish fine phonetic details in speech (Houston, Pisoni et al., 2003).

Results from older cochlear implant users' speech feature discrimination abilities indicate that they may not encode specific phonetic detail in early representations (Pisoni et al., 1999). Results also indicate intergroup variability based on speech feature discrimination in word recognition tasks. Even in a "best case scenario", cochlear implant users may still have trouble discriminating speech features such as place of articulation. Though discrimination improves over time, "low performers" struggle to discriminate voicing and place of articulation even after 5 and 6 years of implant use. If the notion of activation and competition between lexical representations is true, difficulties discriminating between consonant contrasts may impede a cochlear implant user's ability to retrieve the correct phonological representation from memory in word recognition and word learning tasks.

Though discrimination abilities improve over time, children with cochlear implants still do not perform at the same levels as peers with normal hearing. It is possible that differences in attention to speech cause cochlear implant users to develop sensitivities to differences in place, manner, and voicing more slowly. It is also possible that cochlear implant users can detect differences in phonemes when they vary by enough features (place, manner, and voice), but not when they differ minimally (i.e. by place manner or voice).

Given that word recognition involves requires the ability to attend to, identify, and discriminate phonetic details in the speech signal (Boothroyd, 1970, 1997; Eisenberg, 2007), differences in auditory processing, attention to sound, and sound discrimination may impact the ability to segment and recognize words in fluent speech. Though impaired, cochlear implant users do have the ability to discriminate between consonant contrasts in isolated word lists (Pisoni et al., 1999). What do we know about their ability to segment continuous speech into individual word units? Now that we have looked at how infants develop the ability to discriminate speech sounds we can move on to aspects of phonological development and word recognition. In Chapter 4 we will discuss how infants become sensitive to word boundaries for segmenting speech and the perceptual sensitivity contained in early lexical representation as well as the processes infants use in selecting stored representations from memory in word recognition tasks.

Chapter 4: Phonological Development and Word Recognition

At the first stages of the language acquisition process, children must pick up on differences between speech sounds and phonetic detail function within a language to encode meaning as well as segment continuous speech into individual, meaningful units for word recognition and learning (MacKain, 1982). Phonological development refers to the development of a system for how sounds are organized and used in a language, including the way in which sound variations function within that language to encode meaning, and it is often considered a prerequisite for word learning (Trubetzkoy, 1969). In other words, phonological development includes aspects of phrase and sentence sound structure, such as prosody and intonation, in addition to differences in speech sounds. Differences in phrasing and phrasal stress display qualitative distinctions which are related to qualitative distinctions in interpretation of language (Pierrehumbert, 1990). For example shifting phrasal stress can change truth conditions (i.e. "I said SAMMY likes vanilla." versus "I said Sammy likes VANILLA") (Rooth, 1985). One way the process of spoken word recognition can be described, is as the process of perceiving and interpreting input in the shape of an auditory stimulus and matching it with a single representation chosen from an array of alternatives in the mental lexicon (Luce & Mclennan, 2008).

This chapter discusses what happens in the first year of life with regards to children's earliest perceptual abilities. Logically speaking, very young infants do not actually understand the meaning of words they hear. Before they can begin to understand the meanings of words, children must be able must differentiate between sounds that his or her language uses in words. Importantly, children must be able to understand where word boundaries are in fluent speech.

The first section of this chapter will examine children's developing abilities to segment speech based on perception of linguistic properties such as rhythmic cues, allophonic variation, and transitional probabilities. Next, additional factors affecting word recognition, such as executive processing, and the implications this may have for cochlear implant users will be discussed. Cochlear implant users may differ from typically developing children in the way they encode and store phonological representations (Pisoni, Clearly, Geers, & Tobey, 1999). It is possible that differences in working memory and verbal rehearsal may account for variability in word recognition in children with hearing impairment (Pisoni et al., 1999; Pisoni & Clearly, 2003). To conclude this chapter, a brief overview of current models of spoken word recognition and support for these models will be provided. Rather than discuss a list of specific models, which would be very extensive, the section will focus on the general notion that the majority of these models operate under; activation and competition. Almost all current models of spoken word recognition operate under the assumption that the perception of spoken words involves both activation of lexical representations in memory and competition between similar representations (e.g. Allopena, Magnuson, & Tanenhaus, 1998; Connine, Blasko, & Titone, 1993; Luce, Goldinger, Auer, & Vitevitch, 2000; Luce & Pisoni, 1998). Together, this overview of research on children's phonological development and early word recognition will give some insight into how lexical representations are typically retrieved from memory and will allow us to draw conclusions on how phonological development, working memory, and lexical effects may impact the ability to recognize and learn words in children with cochlear implants.

SPEECH SEGMENTATION

The ability to segment words in fluent speech is a necessity for language learners since words are rarely spoken in isolation (Saffran, Aslin, & Newport, 1996). Even when caregivers are teaching children words, words are only presented in isolation approximately 20% of the time (Woodward & Aslin, 1990), although recent research has revealed that a much higher percentage of words have a clear sentence or phrase boundary at one end (Johnson, 2012; Van Heugten & Johnson 2012 REF). When segmenting words from fluent speech, infants are initially not interpreting the meanings of words or sentences, but are merely listening for patterns within the speech stream. Without knowing where words begin and end, infants cannot begin to form lexical representations from fluent speech needed for word learning. How do infants learn about word boundaries? Evidence has shown that infants as young as 7.5 months of age are able to segment words from fluent speech (Jusczyk & Aslin, 1995) and begin perceiving differences in suprasegmental features such as rhythm and prosody by 9 months of age (Jusczyk, Cutler, & Redanz, 1993; Nazzi, Dilley, & Jusczyk, 2003). By 10 months of age, infants are able to segment words based on allophonic information (Jusczyk, Hohne, & Bauman, 1999, Mattys & Jusczyk, 2001), coinciding with the shift towards language-specific speech discrimination which was discussed in Chapter 3 (Best, 1994; Best, McRoberts, Lafleur, R., & Silver-Isenstadt, 1995; Werker & Tees, 1984).

Rhythmic properties such as stress and prosody are used by adults to indicate word meaning and word boundaries (Houston, 2008; Pierrehumber, 1990; Rooth, 1985). Infants aged 7.5 months are able to segment strong/weak words in fluent speech, but are unable to segment words with a weak/strong pattern. This may be because infants are more likely to expect and listen for words conforming to the typical strong/weak stress pattern and it may not be until more language exposure that they begin to recognize the less common patterns (Jusczyk, Houston, & Newsome, 1999). Using a version of the *Headturn Preference Procedure* (Kemler Nelson et al., 1995), 7.5-month-old infants were tested on their ability to segment weak/strong words in fluent speech. Infants were familiarized with 7.5 month olds with pairs of weak/strong words (i.e. ‘‘guitar’’ and ‘‘surprise’’) and tested them within passages. Mean listening times for passages containing the familiar words and for the ones containing the unfamiliar words were averaged. 7.5-month-old infants were unable to detect the familiarized words within the passages. This indicates that at 7.5 months of age, infants are not necessarily aware of actual words, but are already segmenting speech based on common stress patterns.

English-learning 9-month-olds were tested for their preference for prosodic stress patterns by examining their preference for bisyllabic words following the traditional strong/weak pattern of English compared to a weak/strong pattern. Nine-month-old English-learning infants attended significantly longer to words with strong/weak stress patterns than with weak/strong patterns; however, 6-month-old infants showed no significant preference for the predominant stress pattern suggesting that between the ages of 6 and 9 months, infants begin to recognize the prosodic features of their native language (Jusczyk, Cutler, & Redanz, 1993).

Nazzi, Dilley and Jusczyk (2003) studied 10.5-, 13.5-, and 16.5-month-olds on their ability to segment verbs. Verbs typically follow a weak/strong prosodic pattern rather than the typical strong/weak pattern used in English. The ability to segment weak/strong verbs was not present until 13.5 months of age. The authors suggest that this may be a reflection of infants' understanding of nouns and social expressions. Infants may also be using lexical and syntactic knowledge in addition to prosodic knowledge by this age.

Taken together, these between the ages of 6 and 9 months of age, infants develop sensitivity to language specific prosodic properties and use these to segment speech (Houston, 2008). Infants get increasingly more attuned to specific prosodic patterns as they age and may even incorrectly segment words across word boundaries based on stress patterns. Infants may also begin using knowledge about other aspects of language to help segment individual words from speech (Nazzi et al., 2003). The development of these speech segmentation abilities in children with normal hearing are all happening at a time when children later implanted with cochlear implants are not getting any auditory input yet. It is possible that following implantation, these abilities develop in a similar manner or even at a faster rate because infants are older and cognitively more developed leading them to possibly pick up on cues faster. Alternatively, it may be that cochlear implant users take longer to develop these abilities because of the reduced richness of the auditory signal.

Various studies have also examined the ability of infants to segment words based on variations of a phoneme (i.e. allophonic differences) (Jusczyk, Hohne, & Bauman, 1999; Mattys & Jusczyk, 2001). Twenty-four 8.5-month-old infants were familiarized with repetitions of two consonant-vowel-consonant words produced in isolation ("dice" and "cash" or "boats" and "seals"). Infants were presented with sentences containing the sound pattern of one of the target words embedded across a word boundary, meaning the target word (i.e. cash) never appeared but there was a production ending in /k/ followed by "ash" ("Builders sometimes *pack ash* in basements"), or passages containing the actual words (Mattys & Jusczyk, 2001). Infants' ability to identify word boundaries was assessed using a *Headturn Preference Procedure* (Kemler Nelson et al., 1995). In a *Headturn Preference Procedure*, the infant is seated on a caregivers lap inside a three-sided booth with loudspeakers mounted on the sides. A small red light is placed near the loudspeaker on each side. The center panel has a green light mounted on it. During the experiment the infant's attention is drawn to the center by flashing the green light. Following this, a red flashing light on one side blinks. When the infant turns to the light, an auditory stimulus begins to play. Presentation of the stimulus is continued until the infant looks away for at least 2 seconds and the infant's total looking time towards the flashing red light is recorded.

The authors hypothesized that if infants analyze input based on phonemic patterns alone, meaning occurring in order, they shouldn't show a preference for passages with the actual words over passage with the pattern of the target word embedded across word boundaries. There was significant difference in listening time between passages containing the target word and those containing the phonemic pattern across word boundaries suggesting that infants use allophonic information to segment words from fluent speech even in the presence of a phonemic match across word boundaries.

Using Kemler Nelson and colleagues (1995) version of the *Headturn Preference Procedure*, 9-month-old and 10.5-month-old infants were familiarized with one word from a pair of acoustically similar two-syllable items ("nitrates" and "night rates") and an additional unrelated word. Nine-month-old infants familiarized with "nitrates" were just as likely to attend to a passage containing "night rates" as "nitrates", but the older infants were able to rely on allophonic cues in fluent speech to locate the familiarized target word rather than the acoustically similar foil within continuous speech (Jusczyk, Hohne et al., 1999). These results provide evidence that infants of this age are sensitive to word-boundaries, even within an embedded familiarized pattern. This finding supports the hypothesis that infants do more than extract speech patterns for segmentation of words (Mattys and Jusczyk, 2001). The fact that infants use allophonic information for segmentation suggests that they are sensitive to language specific properties of phonemes, such as variations in phonemes, by 10.5 months of age.

In addition to using phoneme specific information, one line of research investigates the theory that infants are able to learn how to segment words from fluent speech based on likelihood patterns such as transitional probabilities, measurable statistical regularities that distinguish recurring sound sequences in words and more "accidental" sequences across word boundaries. For example, the sound sequence /tk/ is unlikely to occur within a word; however, it may occur across a word boundary like in “fit kid”. The use of transitional probabilities in segmenting fluent speech was assessed in a group of twenty-four 8-month-olds using a familiarization-preference procedure (Jusczyk & Aslin 1995). In a familiarization-preference procedure, infants are first familiarized with a set of stimuli. During testing, infants are presented with two types of stimuli: items contained from the familiarization phase and novel items that are highly similar to familiarization items. Similar to the *Headturn Preference Procedure* (Kemler-Nelson et al., 1995) infants’ sustained visual fixation on a blinking light corresponding to the auditory stimuli is assessed.

Infants were familiarized with 2 minutes of continuous speech consisting of 4 three-syllable nonsense words (i.e. bidaku) repeated in random order. The continuous speech stream (i.e. bidaku/padoti/golabu/bidaku), which contained no acoustic or prosodic cues to word boundaries, was produced using a synthesizer and imitated a monotone female voice. The only cues to word boundary were transitional probabilities which were 1.0 within words (i.e. bida) and .33 between words (i.e. kupa). Infants were then presented with repetitions of 4 three-syllable nonsense words: one of the familiarized nonsense words and two novel nonsense words. Infants attended significantly longer to the nonsense words they had been familiarized with than the novel nonsense words (Saffran, Aslin, & Newport, 1996). This indicates that the infants were able to segment the nonsense words presented in the continuous speech stream by extracting serial ordering information suggesting that infants’ word segmentation abilities are not necessarily dependent upon acoustic and prosodic cues.

Additional studies on transitional probabilities have found that 6- to 7-month-old infants rely more on transitional probability (Thiessen & Saffran, 2003) while 8- and 9-month-old infants are more reliant on stress than transitional properties in word recognition (Johnson & Jusczyk, 2001; Thiessen & Saffran, 2003). This result suggests that transitional probability may be the initial method used for segmenting words until enough phonological knowledge has been acquired (Houston, 2008). It is possible that syllable stress may constrain infant computation of transitional probability. English-learning infants may also be responsive to the fact that words tend to begin with stressed syllables based on hearing words in isolation (Houston, 2008).

Dutch-learning 5.5- and 8-month-old were assessed on their ability to use transitional probabilities for word segmentation using the *Headturn Preference Procedure* designed by Saffran and colleagues (1996). In this study, two artificial languages were used: UWL condition (consisting of four disyllabic words) and MWL condition (consisting of two disyllabic and two trisyllabic words). Mean looking times for both age groups and both language type conditions were recorded. In the UWL condition, 16 of the 24 5.5-month-olds and 16 of the 24 8-month-olds looked longer to part words than words. In the MWL condition, 12 of the 5.5 month-olds and 14 of the 8 month-olds oriented longer to part words than to words. Both groups of infants could segment words when they were all of the same length, but could not do so when the words were of varying lengths. This suggests that removing the regularity of the words hindered infants' ability to segment using transitional probabilities (Johnson & Tyler, 2010)

This body of research evidences the developing phonological system and infants' abilities to perceive phonological distinctions. The ability to segment words and clauses from fluent speech is present as early as 8 months of age, indicating that by this age lexical representations formed from words in isolation are generalized to connected speech (Houston et al., 2000; Jusczyk & Aslin, 1995; Jusczyk, et al., 1993; Jusczyk, Houston et al., 1999). This finding is of importance because the majority of word learning results from fluent speech heard in the environment (Jusczyk & Aslin, 1995). The fact that infants' abilities to segment weak/strong patterns is not evidenced until 13.5 months of age (Nazzi et al., 2003) may reflect infants' increase in lexical and syntactic knowledge. If segmentation abilities of less common prosodic patterns are based on other types of knowledge and amount of language exposure, this could have implications for cochlear implant users, especially those implanted at later ages who have endured a period of auditory deprivation resulting in less language exposure. Results also indicate that by 10 months of age, infants become sensitive to allophonic information and no longer rely solely on phonemic patterns to segment words from fluent speech, even when words follow a similar phonemic pattern (i.e. "nitrates" and "night rates"). Results on transitional probabilities (Johnson & Jusczyk, 2001; Saffran et al., 1996; Thiessen & Saffran, 2003) indicate that young infants may rely more on phonemic sequencing constraints on ordering in segmenting fluent speech, while older infants may have access to more phonological knowledge to segment words based on finer phonetic distinctions.

This period of early infancy during which children with normal hearing are acquiring the ability to segment words from fluent speech occurs at a time before the majority of cochlear implant users have been implanted. Without access to auditory information, cochlear implant users cannot begin to develop sensitivities to rhythm and prosody or to allophonic variation. Not all cochlear implant users are implanted at 6 months of age, meaning that a majority will be missing out on a period of time when segmentation abilities begin to develop. Even if implanted at 6 months of age, cochlear implant users are still 6 months behind typically developing children.

To date, no studies assessing word segmentation abilities in children with hearing impairment have been conducted. Based on studies of typically developing children, we know that a lot of learning goes on in the first year of life. Can infants with longer periods of auditory deprivation catch up to typically developing children once they have access to sound? It is unknown whether children with hearing impairment develop sensitivities to rhythmic and prosodic cues as children with normal hearing do. Even if they do, it is possible that sensitivity to suprasegmental information may be delayed due to auditory deprivation, since this ability does not seem to develop until 7.5 months after birth in children with normal hearing. It is possible that the period of auditory deprivation may cause cochlear implant users to develop these abilities at a slower rate than children with normal hearing. Also, cochlear implant users are chronologically older once they gain access to sound. This difference in general cognitive development may allow them to begin detecting patterns faster than children with normal hearing, resulting in rapid acquisition of speech segmentation abilities. On the contrary, a more developed cognitive system may hinder development of the detection of speech patterns. Children that are more cognitively advanced may be less interested in speech and speech patterns.

It is also unknown whether children with hearing impairment are able to use allophonic cues to segment words. If the ability to segment words following a less common prosodic pattern, such as weak/strong, is dependent on additional language knowledge, such as semantic and syntactic knowledge, children with hearing impairment may also be delayed in this aspect due to reduced language exposure. The most important finding from this body of evidence is that young infants with normal hearing are able to segment words in continuous speech even in the absence of prosodic and allophonic cues by using transitional probabilities. If children with hearing impairment do not have access to suprasegmental and allophonic cues, they may be able to rely on transitional probabilities of sound sequences to segment words. Again, no research has been conducted in this area. Even though the ability to discriminate speech features and segment words from fluent speech does not mean that infants are attaching meaning to words it does indicate that they are learning about patterns within words and fluent speech. If children do not know where word boundaries occur, they will have difficulty isolating words they hear and may have trouble learning words. In addition to possible speech segmentation differences, what additional factors may affect cochlear implant users' ability to recognize words and begin developing a lexicon?

ADDITIONAL FACTORS IN WORD RECOGNITION

Studies on typically developing children have shown correlations between working memory capacity and the ability to learn to recognize and understand new words

(Gathercole, Hitch, Service, & Martin, 1997; Gupta & MacWhinney, 1997). Vocabulary development and other speech and language milestones have been shown to be associated with differences in working memory, including digit span which reflects processing capacity (Gathercole & Baddeley, 1990). Typically developing children may use serial scanning and retrieval of items from short-term memory as well as subvocal rehearsal of phonological information for recalling words, affecting working memory capacity (Cowan, Wood, Wood, Keller, Nugent, & Keller, 1998). It has been suggested that some of the variation in outcomes in cochlear implant users may be related to how sensory input is processed (Pisoni et al., 1999). Therefore, it is imperative to understand the effects of differences in working memory on word recognition abilities in children with normal hearing. The following section will investigate correlations between a variety of working memory tasks, such as forward and backward digit span tasks, speech rate, and verbal rehearsal, and word recognition abilities. In addition, word recognition abilities in cochlear implant users will be further investigated by dividing the group based on communication mode: orally trained versus total communication. These studies will give us further insight into what additional affects prolonged auditory deprivation may have on the development of executive functioning abilities as well as what factors may account for differences in cochlear implant users' outcomes.

Digit Span

To analyze working memory, the *Wechsler Intelligence Scale for Children-Third Edition* (WISC-III) (Wechsler, 1991) was used to collect forward and backward digit spans from 176 8- and 9-year-old deaf children. The data was compared to 45 age-matched peers with normal hearing. In a forward digit span task, the individual is presented with a list of digits and required to repeat that list back to the examiner in order. In backward digit span tasks, an individual is presented with a list of digits but is required to repeat it back backwards. For both tasks, digit span begins at two items and increases in length until a child gets two lists of the same length wrong (Pisoni & Clearly 2003).

Forward digit spans reflect coding strategies related to phonological processing and verbal rehearsal that are used to maintain information within short-term memory whereas backward digit span tasks reflect the controlled attention and operation at the executive functioning level (Rosen & Engle, 1997; Rudel & Denckla, 1974). The forward digit span for typically developing children was significantly longer than the forward digit span of cochlear implant users, demonstrating an atypical development of deaf children's short-term memory capacity. This finding suggests a possible difference in underlying processing mechanisms used in encoding and maintaining sequences of spoken digits in immediate memory (Pisoni & Clearly, 2003).

To explore this phenomenon further, data was analyzed relative to communication mode. Cochlear implant users immersed in oral environments had a longer forward digit span than those in total communication environments. This was not true for backward digit tasks. This difference suggests coding and verbal rehearsal processes involved in forward digit span conditions may be related to effects early sensory and linguistic experience have on immediate memory. It is difficult to isolate which information processing mechanisms are inhibited by reduced experience early on and which are responsible for increases in forward digit span exhibited by these children (Pisoni & Clearly, 2003).

To determine if there is a relationship between working memory capacity and spoken word recognition in cochlear implant users, scores from the WISC-III forward and backward digit spans were correlated to three measures of word recognition: Word Intelligibility by Picture Identification (WIPI) (Ross & Lerman, 1979), Lexical Neighborhood Test (LNT), (Kirk, Pisoni, & Osberger, 1995) and the Bamford-Kowal-Bench (BKB) (Bench, Kowal, & Bamford, 1979) sentences test. The WIPI is a closed-set test of word recognition in which the child selects a word from a set of six pictures. Like the LNT, the BKB is an open-set word recognition tests, however key words are presented in sentences rather than in isolation as on the LNT. Data analysis showed that children with longer digit spans, both forward and backward, outscored other children on all three measures of word recognition (Pisoni & Clearly, 2003). This finding indicates that both coding strategies related to phonological processing and verbal rehearsal as well as attention and operation at the executive functioning level are necessary for word recognition and that deficits in these areas may result in reduced word recognition abilities.

Overall, forward and backward digit span tasks indicate that there may be some differences in the way cochlear implant users process information in working memory. If forward digit spans are indeed reflective of strategies used to maintain information within short-term memory, it is possible that these differences in memory capacity could help explain some of the wide variation seen in cochlear implant users, even between cochlear implant users that have had the same amount of language exposure and experience. However, these measures all assessed verbal working memory and correlated it to word recognition abilities. What about general working memory? It is possible that cochlear implant users have normal working memory and it is the verbal aspect of such tasks that caused the differences. To determine if this is the case, verbal and non-verbal working memory should be assessed in cochlear implant users. If they perform the similarly on both, it can be assumed that the deficit lies in general working memory. If they perform better on non-verbal working memory tasks, it would indicate that it is the nature of the task (verbal versus non-verbal) that is causing the difference. This would then suggest that cochlear implant users do not necessarily differ in their executive functioning abilities. Additionally, comparing verbal working memory scores to infants that are matched by hearing-age would allow us to determine if verbal working memory is slower to develop in cochlear implant users or if the discrepancy between age-matched peers and cochlear implant users is truly due to working memory differences. Additionally, these results do not provide us with much information about working memory outcomes in infants implanted before 1 year of age. A study assessing working memory abilities in cochlear implant users implanted prior to age 1 compared to those implanted at 1 year old or even later would provide additional insight into whether early auditory experience affects working memory capacity. Conducting such a study assessing both verbal working memory and general working memory would allow us to further determine if differences in verbal working memory as well as general working memory differences are affected by implantation age. It may even be that earlier implanted children do not show deficits in verbal working memory at all which would allow us to conclude that longer periods of auditory deprivation in cochlear implant affect the extent working memory deficits.

Speech Rate

Studies on children with normal hearing have indicated that speech rate is correlated with verbal rehearsal, which may also be a reflection of executive functioning such as working memory capacity (Baddeley, Thompson, & Buchanan, 1975; Cowan et al., 1998). This correlation reflects either articulation speed used to maintain phonological patterns in working memory, or the time needed to retrieve information already in working memory (Cowan et al., 1998). Interword pause time has been shown to provide a reliable measure of memory scanning and retrieval dynamics and that interword pauses in immediate recall increase as the length of the word list increases (Cowan, Keller, Hulme, Roodenrys, McDougall, & Rack, 1994). Children with shorter interword pauses have been shown to have longer immediate memory spans (Cowan et al., 1998).

To further evidence these findings, speech production samples consisting of three sets of meaningful English sentences, using stimulus materials and experimental procedures developed by McGarr (1983), were collected (Pisoni & Clearly, 2003). Sentences were analyzed for duration and speaking rate and then correlated to digit span and word recognition abilities of the participants. Children (both cochlear implant users and children with normal hearing) who produced sentences with longer durations spoke more slowly and had shorter forward digit spans. Slower speaking rates were associated with poorer word recognition scores on all three word recognition tests (WIPI, LNT, and BKB). Results indicate no differences between cochlear implant users and children with normal hearing in average duration of articulation of individual digits or response latencies at any list length, but interword pause duration differed among groups. The average individual pauses in the forward digit span task were significantly longer in cochlear implant users than in typically developing children at lengths of 3 and 4 digits. Overall, cochlear implant users had shorter digit spans and longer sentence durations than children with normal hearing in addition to much longer interword pause durations, reflecting slower serial scanning processes. This indicates that slower subvocal rehearsal and serial scanning are associated with shorter digit spans in cochlear implant users.

Taken together, results show an atypical development of short-term working memory capacity in cochlear implant users and that cognitive processing may account for the range of outcome measures following implantation and cochlear implant use. The information processing mechanism used in encoding, maintaining, and retrieving phonological information is affected by the environment and experiences young cochlear implant users are exposed to. Reduced exposure to speech and language may affect the development of automatic attention and the speed at which speech can be identified and encoded as stable phonological representations in short-term memory. Cochlear implant users require active engagement in spoken language processing and passive exposure to speech may not be enough for the development of strong lexical representations. Differences in processing information and short-term memory capacity and the relationship between word recognition abilities is an additional important area in which more research needs to be conducted. As with digit span tasks, speech rate and interword pause time are reflections of verbal working memory, not general working memory. Additional research involving general working memory capacity would allow us to know for sure whether working memory capacity is only affected when related to the processing of verbal information.

Now that we know that there may be differences in how typically developing children and cochlear implant users process and encode auditory information, we need to determine how these differences might affect retrieval of lexical representations from memory. How do typically developing children retrieve lexical representations from memory? What perceptual features might they encode in these early mental representations and use for word recognition and recall?

WORD RECOGNITION AND RECALL MODELS

Multiple word recognition models have been created to help explain and understand the process used in selecting words from the lexicon in word recognition tasks. The following section will discuss word recognition models in some detail, but the list is by no means exhaustive. differences in executive functioning, such as working memory and verbal rehearsal, can affect processes such as lexical retrieval (i.e. Cowan, Wood, Wood, Keller, Nugent, & Keller, 1998; Pisoni & Clearly, 2003; Pisoni, Clearly, Geers, & Tobey, 1999). Current models of word recognition suggest the notion of radical activation and competition between activated representations. Radical activation proposes that form-based representations that are consistent with the stimulus input may be activated at any point in the speech stream. Any consistency between input and representation may result in some degree of activation (Allopena, Magnuson, & Tanenhaus, 1998; Connine, Blasko, & Titone, 1993; Houston, 2008; Luce, Goldinger, Auer, & Vitevitch, 2000; Luce & Pisoni, 1998). It has been posited that there is specialized neural assembling that is dedicated to extracting linguistic information from speech and ignoring indexical properties of the signal (Sussman, 1984; 1986). Based on this view, only information such as phonetic properties would be used in word recognition and properties such as talker gender would be ignored.

One example of an activation-competition model is the neighborhood activation model (NAM) (Luce & Pisoni, 1998). According to this model, auditory input activates a set of acoustic-phonetic patterns in memory. Patterns are activated based on the degree to which they match the perceived input. High neighborhood density has effects on processing time and accuracy in speeded single word shadowing, auditory lexical decisions, and perceptual identification (Luce & Pisoni, 1998). Findings from studies on the effects of priming on word recognition suggest that when a word has high neighborhood density (a collection of words similar to a given target words), the human brain requires more time to process that word (i.e. weed out similar sounding words) in order to recognize the intended word (Allopena, Magnuson, & Tanenhaus, 1998; Connine, Blasko, & Titone, 1993; Luce, Goldinger, Auer, & Vitevitch, 2000; Luce & Pisoni, 1998).

Whether or not representations of spoken words in memory are activated by similar sounding non-words was investigated using a cross-modal priming paradigm (Swinney, 1979). In cross-modal priming tasks, participants listen to words in isolation or in sentences while being presented with visual probe words related semantically to the auditory stimuli. The auditory stimulus is intended to prime the visual probe word. Participants are required to respond to the visual probe, usually by making a lexical judgment, and response time is recorded.

One-hundred-twenty bisyllabic words following the strong/weak pattern and visual targets that were related or unrelated to the target word were selected (Connine, Blasko, & Titone, 1993). The target words were divided into two lists containing an equal number of high and low frequency words. Three additional lists of 120 non-words were created; in two lists, the non-words differed in initial phoneme either minimally (differing by 2 or less linguistic features i.e. “many” became “tany”) or maximally (differing by at least 4 linguistic features i.e. “number” became “kumber”), in the third list of non-words, the phoneme in medial position was altered (i.e. “detail” became “dekail”). Presentation of the words was followed by a visual display that was related or unrelated to the real word. Subjects were instructed to press one of two buttons to indicate whether the visual target was a word or a non-word. Results indicated that non-words that differed minimally, either by initial or medial consonant, resulted in significant priming effects when a picture semantically related to the target word was presented. Non-words that differed maximally showed no priming effects for semantic associations suggesting that competitor activation is not dependent on overlap in initial position, meaning that phonetic information from anywhere within the word could be used to activate stored representations.

Allopena, Magnuson, & Tanenhaus, (1998) presented participants with various pictures on a computer screen and asked them to use a mouse to click on a picture of a specific word. Analysis of eye movements indicated that rhyming competitors activated early on in recognition process, even when word-initial information was different. For example, when asked to select a picture of “beaker”, participants’ fixation probabilities indicated they also considered a picture of “speaker”. This shared word-initial information is not necessary to activate competitors (). Studies assessing recognition time using primes and targets that were phonetically similar, but not position specific (i.e. shun and gong) indicate that shadowing times are significantly slower for target words that follow a phonetically related prime than for target words following an unrelated prime. This suggests that phonetically related primes actually hinder rather than facilitate response time providing further support for the activation-competition framework (Luce, Goldinger, Auer, & Vitevitch, 2000).

There are, however, challenges to this idea of competitor activation models. One potential problem is that they do not account for surface details, such as talker specific information. Radical activation models assume that lexical items are represented only by abstract phonological codes and indexical variation is treated as irrelevant. Competitor-activation models propose that input is mapped onto features, allophones, phonemes, or some combination of these three to construct form-based representation. Differences in spoken words differing by more physical dimensions such as talker gender would not be captured in these representations. In order for infants to recognize words, stored lexical representations must contain enough detail for precise recognition, but be general enough not to be affected by normal variability in articulation (Houston & Jusczyk, 2000; 2003; Jusczyk & Aslin, 1995; Swingley & Aslin, 2000). In other words, representations in the mental lexicon must contain specific phonetic information, but not be so specific that variation in indexical properties inhibits their recall.

Exemplar approaches posit that infants encode both phonetic and indexical details of sound patterns of words in their mental lexicons (Luce & McLennan, 2008). For example, the Word Recognition and Phonetic Structure Acquisition Model (Jusczyk, 1993; 1997) posits that in the first level of infant speech perception, auditory analyzers pick up auditory input and provide spectral and temporal description. A weighting scheme is then developed, giving prominence to features needed to understand the infant's native language. Potential word candidates are extracted from fluent speech and stored in lexical retrieval. This model proposes that new instances of the same word may not be recognized as similar because relatively few exemplars have been encoded. Acoustically different instances of the same word may be treated as different words until infants develop a mental lexicon large enough and containing enough examples for them to extract both linguistic and talker-specific information (Houston, 1999; Houston & Jusczyk, 2000; 2003).

The proposal that indexical information is ignored in early lexical representations (Sussman, 1984, 1986) has been contradicted by evidence that speaker variability does have an effect on word recognition abilities early in development (Houston, 1999; Houston & Jusczyk, 2000; 2003). The ability to recognize words in passages produced by talkers of opposite sex was assessed in 7.5- and 10.5-month-old infants. Ten-and-a-half-month-olds were able to recognize familiarized words in passages when produced by a talker of a different gender while the younger infants could not (Houston & Jusczyk, 2000). This talker-specific information may serve as an important cue early on in word retrieval.

Using the *Headturn Preference Procedure* (Kemler Nelson et al., 1995), 7.5-month-old infants were familiarized with 2 words and tested on the next day for their orientation times to 4 passages, 2 of which contained the familiarized words. At 7.5 months of age, infants oriented significantly longer to passages with familiarized words when they were produced by the original talker. Infants did not attend longer to the passages with familiarized words when the passages were produced by different talkers of the same sex (Houston & Jusczyk, 2003). To explore this phenomenon further, 7.5-month-olds and 10.5-month-olds were familiarized with words from one talker and tested them the following day based on two passages produced by the original talker and two produced by a different talker of the same sex (Houston & Jusczyk, 2003). Infants recognized familiarized words produced by a familiar talker and for those produced by a novel talker, contradicting the findings from earlier in the study. It is possible that the presence of a familiar talker during testing helped with word recall so the infants were able to subsequently recognize words produced by a new talker. This result indicates that talker-specific information may facilitate word recall in infants (Houston & Jusczyk, 2003). When infants were familiarized and tested with words and passages produced by perceptually similar talkers of the same sex they were able to recognize words produced by a novel talker. When these infants were tested with talkers relatively different perceptually from the familiarization talker, infants did not recognize words produced by the novel talker, even when they were of the same gender (Houston, 1999).

Overall, results from studies investigating speaker variability effects on word recognition recall in infants (Houston & Jusczyk, 2003). These indexical properties might have an effect on an infant's ability to recognize words and generalize word representations to various contexts. Infants' representations of sound patterns may become more robust and generalizable when they are familiarized with words in which the distribution of talkers is relatively large with respect to perceptual similarity (Houston, 1999; Houston, 2008). Infants may also generalize representations of words when they are exposed to exemplars produced by a variety of talkers (Houston, 2008). This could have implications for children with cochlear implants who have had limited access to language and may not have been exposed to as many exemplars of words as children with normal hearing. If variations in talker variability facilitate word recall and effect an infant's ability to recognize words in various contexts, children with hearing impairment who have not been exposed to as many variable productions of a word may be unable to recognize familiar words in new contexts. If they hear a familiar word produced by a perceptually different talker, they may encode this word as being different word until they have heard enough differing productions to realize that they are in fact the same word.

Discussion and Conclusions

The developing ability of children with normal hearing to segment words from fluent speech using cues such as rhythmic and prosodic patterns, allophonic variations and transitional probabilities has been studied in typically developing children, yet no such evidence exists for children with hearing impairment; an area in which further research is needed. Word segmentation abilities are developing during a time which most children with hearing impairment have not yet been implanted. Additionally, difference in general cognitive development based on actual age differences may either allow cochlear implant users to become sensitive to patterns faster than children with normal hearing, or result in less interest to these rhythmic patterns. Speech segmentation research in children with normal hearing who are chronologically older may help us determine if differences in general cognitive development affect attention to such patterns. If segmentation abilities of less common prosodic patterns (i.e. weak/strong) are based on language knowledge and amount of language exposure (Nazzi et al., 2003), this could have implications for cochlear implant users, especially those implanted at later ages, who have endured a period of auditory deprivation resulting in less language exposure and reduced semantic and syntactic knowledge. To date, we do not know exactly how much semantic and syntactic knowledge cochlear implant users may have when they reach similar hearing ages or how rapidly they can acquire such knowledge. Research investigating various aspects of general language knowledge in cochlear implant users may help us to determine how sensitive they are to semantic or syntactic information.

Results from working memory studies indicate an atypical development of short-term working memory, which may account for differences between children with normal hearing and those with hearing impairment as well as some of the intergroup variability in cochlear implant users. Studies assessing word learning abilities based on phonetic similarities show that children with normal hearing may not be able to perceive different contrasts in word learning tasks, even if they can do so in discrimination tasks, due to high computational demands. If infants are unable to use phonetic detail when the processing load of a task, such as word learning, is too high, this may further delay cochlear implant users' abilities to learn words. As previously mentioned, digit span, speech rate, and interword pause time assess only verbal working memory, not general working memory. Without conducting research to determine if cochlear implant users have normal general working memory, we cannot say for sure that the differences in verbal working memory are related to executive functioning deficits or if the differences are related to the addition of verbal information to the task. Furthermore, knowledge of how cochlear implant users vary based on age of implantation and how they compare to hearing-age peers is necessary to establish whether verbal working memory differences between cochlear implant users and age-matched peers was related to auditory experience or if cochlear implant users are slower and less able to develop verbal working memory skills after gaining access to sound.

Evidence that indexical properties such as talker variability may facilitate word learning and contribute to more robust and generalizable lexical representations may affect children with hearing impairment as they may have less exposure to various models of the same word, possibly leading them to mistake differences in indexical properties as different words rather than variations of the same word. This deficit may lead to mental representations that are in a sense, over specific, and cause children with hearing impairment to have difficulty generalizing representations of words to various contexts or learn new words. If cochlear implant users over-specify early representations and treat variations of the same word as different words, they may be unable to develop strong representations for specific words. This processing difference may give them trouble in word learning later on. For example, if a cochlear implant user has only been exposed to one or two variations of the word "shoe", but is then presented with a slightly altered version during continuous speech, they may not recognize that production as the word "shoe".

We have now covered research on auditory processing, speech discrimination, speech segmentation, as well as the ways in which lexical representations may be retrieved from memory. What do we actually know about the nature of early lexical representations and the information they may contain? Are typically developing infants able to use these representations in word learning tasks? Do cochlear implant users use the same processes as children with normal hearing? Chapter 5 will examine the amount of phonetic detail that infants encode in their early lexical representations and use in word learning tasks.

Chapter 5: Lexical Representations

Phonological specificity in representations has been studied by examining preference for correct versus incorrect productions of words. The following chapter discusses studies assessing the amount of detail in early representations as well as the amount of perceptual knowledge infants perceive and use in learning words. It is possible that cochlear implant users are less able to use phonetic detail in word learning than children with normal hearing due to differences in speech discrimination abilities and working memory capacity. The first section in this chapter will focus on the nature of early lexical representations in children with normal hearing and how differences in task demands may affect their ability to learn novel words. Research on typical development in this area involves mispronunciation detection in word recognition as well as word-learning tasks. The following section will focus on the few word recognition and word learning studies that have been conducted on cochlear implant users. Additionally, research comparing word-learning ability to speech perception and vocabulary size in cochlear implant users will be discussed.

Typical Development

There has been a lot of debate in recent years concerning the nature of early lexical representations, especially concerning the question of whether these representations are detailed or more abstract in nature (Halle & de Boysson-Baries, 1996)

(Jusczyk & Aslin, 1995). Another major topic of debate in this area has been to what extent infants are able to use their perceptual knowledge and abilities when they are acquiring words (e.g. Pater, Stager, & Werker, 1998, 2001; Stager, 1999; Stager & Werker, 1997; Werker, Cohen, Lloyd, Casasola, & Stager, 1998; Werker, Fennell, Corcoran & Stager, 2002). It has for instance been suggested that there is discontinuity between the phonetic representations used in speech discrimination tasks and the phonological representations required for language use (Pierrehumbert, 1990).

In a study using a *Headturn Preference Procedure* (Kemler Nelson et al., 1995) French 11-month-old infants' looking times between altered familiarized words and novel words was examined. (Halle & de Boysson-Bardies, 1996). Infants showed a preference for familiarized over novel words. Familiarized words were then slightly altered (i.e. ponjour for bonjour) and tested again. Infants still showed a preference for the altered familiarized words over novel words. This finding suggests that at this age, representation of words do not contain fine phonetic detail. This supports the discontinuity hypothesis and the idea that children's early lexical representations are holistic in nature. The authors argue that lexical representations are more holistic in nature and less attention is paid to phonetic detail.

The original idea of holistic word representations has however been contradicted by studies showing that infants are able to detect slight mispronunciations in word recognition tasks (Jusczyk & Aslin, 1995; Swingley & Aslin, 2000). Using a combination of word monitoring (Cutler & Norris, 1979; Foss & Swinney, 1973), auditory priming (Tulving & Schacter, 1990), and *Headturn Preference Procedure* (Kemler Nelson et al.,

1995) infants' ability to recognize monosyllabic words in fluent speech was assessed (Jusczyk & Aslin, 1995). Twenty-four 7.5-month-old infants were familiarized with a set of two words: "cup" and "dog" or "feet" and "bike". Infants were presented with sentences containing the familiarized words and those containing novel words. Results indicate significant differences in looking time between the familiarized words and the novel words. This same procedure was used on 6-month-old infants, but they showed no preference for passages containing familiar words indicating that the ability to identify familiarized words in connected speech develops by 8 months of age. Even after only brief exposure, infants are able to store patterns of phonemes and recognize them in different contexts. This also indicates that by this age lexical representations formed from words in isolation are generalized to connected speech.

To extend this finding, another set of infants familiarized with non-words that differed from the real words previously used by place of articulation of the initial phoneme (i.e. "tup" "zeet" "gike" and "bawg" for "cup" "feet" "bike" and "dog") and tested on passages containing the real words (Juszcyk & Aslin, 1995). Infants did not orient longer to passages with the real words after being familiarized with the similar non-words. This suggests that 7.5-month-olds form representations of words containing fine phonetic detail that are generalizable to new instances, but not overgeneralized to phonetically similar non-words.

This has also been evidenced in studies assessing slightly older infants. In a seminal study using a *Preferential Looking Paradigm* (Golinkoff, Hirsh-Pasek, Cauley & Gordon, 1987), 14-month-olds were assessed for attention to a target versus a distractor.

The *Preferential Looking Paradigm* has also been called the *Language-Guided-Looking paradigm* or *Looking While Listening paradigm* in other papers. Infants showed a greater preference for targets when the target word was produced accurately than when it was produced incorrectly (Swingley & Aslin, 2000). Findings were later replicated with a group of 19-month-old Dutch infants using a visual fixation task. Infants were shown pairs of pictures and heard correct pronunciations and mispronunciations of familiar words naming one of the pictures. Mispronunciations involved substituting a /d/, a common sound in Dutch, or a /g/, a more rare sound in Dutch in initial or medial position. Performance was better for correct pronunciations than for mispronunciations involving either substituted consonant (/d/ or /g/), regardless of position (Swingley, 2003).

To establish whether 19-month-olds exhibit sensitivity to varying degrees of phonological mismatch, they were presented with displays consisting of one familiar and one unfamiliar object using an *Intermodal Preferential Looking Paradigm* (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987). Infants were seated on a parent's lap with two television monitors mounted side by side in front of the infant. A speaker and a blue light were mounted between the monitors at infant eye-level. Each trial began with the blue light flashing until the subject fixated at midline. During the salience phase, the two objects were presented simultaneously in the absence of an auditory stimulus to establish baseline looking preferences. Looking time to the familiar versus novel object was recorded. The experimental session consisted of 18 trials, each of which involved a unique familiar object–novel object pair. Of 18 total trials, half involved correct labeling of one object and the other half involved a mispronunciation of the familiar object's label. One-feature mispronunciations involved changes in place of articulation, two-feature mispronunciations involved changes in place and voicing, and three-feature mispronunciations involved changes in place, voicing and manner. All mispronunciations resulted in non-words or in words judged unlikely to be familiar to toddlers at this age.

During the test phase, the same two visual stimuli were presented simultaneously. The first auditory stimulus (‘‘Where’s the X?”) was presented with the visual stimuli. Three seconds after the offset of the target word a second auditory stimulus was presented (‘‘Find the X!”). Looking times between the correct condition and each of the three mispronunciation conditions were significantly different with the greatest difference being for 3 feature changes. Results reveal that 19-month-olds looked significantly longer when mispronunciations involved two or three feature changes, but not when they only involved a change in place of articulation. This suggests that infants are sensitive to varying degrees of mispronunciation.

A possible explanation for the difference in findings is that the infants in the study by Halle and de Boysson-Bardies (1996) were listening to words for information on semantic content, rather than paying attention to phonetic detail in the signal. This may have caused them to adopt a holistic listening strategy, interfering with their ability to encode phonetic detail. The problem with this hypothesis is that task in the experiment did not require infants to listen for meaning. The infants were only tested on their preference for a familiarized word versus a slightly altered version of a familiarized word (Werker, Fennell, Corcoran, & Stager, 2002).

Using an *Intermodal Preferential Looking Paradigm* (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987), 12-month-olds' sensitivity to both vowel and consonant mispronunciations of familiar words was assessed (Mani & Plunkett, 2010). The auditory stimuli presented to infants were nine monosyllabic consonant-vowel-consonant nouns from taken from the *British Communicative Developmental Inventory* (BCDI) (Hamilton, Plunkett, & Schafer, 2000). These words are known by approximately half of 12-month olds, based on norms for the British CDI. The visual stimuli were computer images of the nine nouns. Sensitivity to vowel and consonant mispronunciations was examined separately to determine if vowels and consonants play different roles in lexical recognition (Mani & Plunkett, 2007; Nazzi, 2005; Nespor, Pena, & Mehler, 2003). Vowel mispronunciations involved either a change in height, backness, roundedness, and consonant mispronunciations involved either a change in place, manner, or voicing of the word onset. To prevent infants from using onset consonant information to identify mispronunciations, the visual stimuli were paired with distractor images whose label began with the same onset consonant. Auditory stimuli were presented through two loudspeakers located immediately above the screen and infants' eye movements were recorded. In each trial, infants saw an image of two familiar objects, side by side. The labels for both objects began with the same onset consonant. Infants were told to "Look!" followed by the presentation of a correct pronunciation or mispronunciation of the target image. Eye movements were analyzed for Longest Look (LLK) and Proportion of Target Looking (PTL). LLK is the difference between an infants' longest look towards the target and the distractor. PTL is used to determine the proportion of time infants spend looking at the target.

Results from the vowel mispronunciations suggest that infants displayed an increased preference for the target following correct pronunciations only. Infants were equally sensitive to all three types of vowel mispronunciations. In addition, infants with larger vocabularies were more sensitive to mispronunciations involving backness of vowel than infants with smaller vocabularies. Results from consonant mispronunciations show that infants displayed an increased preference for the target following correct pronunciations and voicing mispronunciations. Unlike with vowels, vocabulary size did not influence infants' sensitivity to consonant mispronunciations. This suggests that language experience may affect infants' sensitivities to vowel mispronunciations. A possible explanation for this difference may lie in the variation in acoustic characteristics.

Vowels vary greatly in their acoustic characteristics while consonants are more easily analyzed (Liberman, Delattre, Cooper, & Gerstman, 1954; Pisoni, 1973). Early lexical representations may be based on the exemplars an infant has been exposed to leading infants to be overly sensitive to variations in vowels. This supports exemplar-based approaches (Jusczyk, 1993; 1997) that variable productions of the same word may be classified as being different until infants have had enough exposure to normal variation in production to consolidate these exemplars into one category.

The effects of bi-directional mispronunciations of place of articulation and voicing were examined in 24-month old Dutch-learning children using a head-turn paradigm (Kemler-Nelson et al., 1995). The hypothesis was that if both members of the contrast were present (i.e. voiced and voiceless cognate or both places of articulation); children should be able to detect the differences (van der Feest, 2007). Infants were presented with voiced mispronunciations of voiceless initial words or voiceless mispronunciations of voiced initial words, or with labial mispronunciations of coronal initial words or coronal mispronunciations of labial initial words. Four pairs of test items, consisting of CVC words, as well as filler items which were constant across groups. All words used in the experiment were known to the children and mispronunciations resulted in non-words or very low-frequency words that were not known to the participants (van der Feest, 2007). The infants were able to detect mispronunciation in familiar words, but could not detect all of the mispronunciations. Word recognition was not affected when word-initial voiced stops were produced as voiceless stops or when word-initial coronal stops were produced as word-initial labials. These results are consistent with studies evidencing that children begin producing voiced stops as voiceless stops and producing coronals as labials early in speech development (ref). Children detected voiced mispronunciations of voiceless words, but they responded similarly to correctly voiced productions and voiceless mispronunciations of voiced target words (van der Feest in print). This experiment was repeated with a group of Dutch-speaking 20-month-olds. Word recognition was affected by place errors when labial initial sounds were mispronounced as coronal sounds, but not vice-versa. The 20-month olds did not detect any mispronunciations of voice for voiced or voiceless targets (van der Feest, 2007).

Overall, results show that by 24 months of age, infants learn that there are voicing and place of articulation contrasts in Dutch, but these contrasts may not be apparent in children as young as 20 months of age. The results also indicate that the direction of feature change plays a role in detecting mispronunciations. Children were able to detect mispronunciations when a labial was mispronounced as a coronal, but not when a coronal was mispronounced as a labial. It may be that this directional affect is due to not perceiving the distinctions sufficiently well; however, because the same labial-coronal asymmetry has been found in Dutch-speaking adults it may be due to under-specification rather than trouble discriminating (van der Feest, 2007).

These previous results looked only at preference for correct versus incorrect productions of familiar words to determine if infants encode phonetic detail in early word representations. Infants may be able to perceive different contrasts in discrimination tasks, but they may not be able to do so in word-learning tasks. Using a *Switch* procedure (Stager & Werker, 1997), infants were habituated to two word-object pairings and tested on their ability to detect a switch in this pairing. 14-month-old infants were able to learn word-object associations involving two dissimilar sounding words (i.e. lif and neem) and looked longer to a trial in which a familiar word was paired with an object previously associated with another target word (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). Canadian 14-month-olds ability to use fine phonetic discrimination for mapping similar sounding words to objects was assessed using a *Switch* task. Infants were able to discriminate between the phonetically similar words (bih and dih), but when they had to discriminate them in a word association task, they could not do so (Stager and Werker, 1997). Stager and Werker's results (1997) were further evidenced in a series of follow-up studies. Even when the words were changed to a more standard form following a consonant-vowel-consonant pattern, (bin and din) (Stager, 1999), when distinctions were based on voicing rather than place of articulation (pin and bin) and when two features, voicing and place, were used (pin and din) (Pater, Stager, & Werker, 1998, 2001), 14-month-old were still unable to discriminate between the two phonetically similar words when required to map these words only objects.

It appears that 14-month-old infants are unable to use fine phonetic detail when mapping novel words to meaning (Pater, Stager, & Werker, 2004; Stager & Werker, 1997; Werker, Fennell, Corcoran, & Stager, 2002). This may be due to discontinuity in representations in speech discrimination and phonological representations of words in the mental lexicon the use of different cognitive perceptual mechanisms for discrimination of a speech sound versus the identification of speech sounds in word learning (Kirk, Pisoni & Osberger, 1995). An additional explanation has been provided: infants are unable to use phonetic detail when the processing load of a task, such as word learning, is too high (Werker, Fennell, Corcoran, & Stager, 2002). When computational demand is high, phonetic detail may be ignored. Infants may focus on forming links between semantic and phonetic information and have less processing resources available to encode fine phonetic details, leading to these seemingly holistic word representations. This suggests that when infants listen to words as acoustic forms only, they are able to discriminate minimal differences, but when they attempt to map the acoustic signal to meaning, they may no longer have enough mental capacities to attend to phonetic detail (Werker et al., 2002).

Results indicating that 14-month-old infants cannot map objects to novel words may reflect the ambiguity of the referential status of the word rather than a lack of fine phonetic detail in early lexical representations (Fennell & Waxman, 2010). Typically, words are presented in isolation in switch tasks. Isolated words are processed less efficiently than words within phrases (Fernald & Hurtado, 2006). In addition, words presented in isolation are typically commands or proper names (Fulkerson & Waxman, 2007; Namy & Waxman, 2000). Evidence has shown that infants can use fine phonetic detail in mapping objects to novel words when it is clear that the word being taught is intended to refer to that object, meaning it has a clear referential status and that presentation of novel words within carrier phrases during word-object mapping tasks can be facilitative (Fennell & Waxman, 2010). Fourteen-month-old infants were presented with recordings of three novel consonant-vowel-consonant words (bin, din, and neem) within seven carrier phrases (i.e. Look. It's the ___.), along with objects moving horizontally across the screen. Infants looked significantly longer on switch than on same trials, suggesting that embedding the novel words in phrases clarified referential status for the infants. With a clear referential status, 14-month-olds were able to use phonetic detail to map the correct words to the intended object.

To rule out perceptual factors, such as coarticulatory cues, as the cause for the success the novel words were produced in isolation, but in a way that maintained referential clarity. If infants are first presented with familiar objects paired with the basic level name (i.e. Kitty or car), they can then map novel words presented in isolation to novel objects (Namy & Waxman, 2000). Fourteen-month-old infants were introduced to three familiar objects (car, shoe, and cat) and were tested based on familiarization to the basic level object name versus exclamation (i.e. Wow) (Fennell & Waxman, 2010). The authors hypothesized that if the ability to map novel words to objects is based on perceptual factors, both infants familiarized with the basic name and the exclamation would fail to map novel words produced in isolation to accompanying objects. Even in the absence of coarticulatory cues, infants familiarized with the basic level name presented in isolation were able to successfully establish word-object mappings; however, those in the exclamation training condition did not. Providing an infant with an exclamation such as “Wow” does not provide a referential cue for the object in the mapping task.

Taken together, these results support the hypothesis that 14-month-old infants do use phonetic detail for word learning and are able to do so at this age when it is clear that the novel word presented refers to the novel object. This also demonstrates that infants can identify referential status using syntactic cues (when presented within carrier phrases) as well as pragmatic cues (when presented in isolation). In other words, 14-month-old infants need to expect that the novel word is going to refer to an object in order to map it accordingly. Fennell and Waxman (2010) interpret these findings as evidence that infants use social, linguistic, and pragmatic information to determine the referential statuses of novel words. Only once this status is inferred, phonetic detail from the novel words can be used in mapping novel words to objects.

If children with normal hearing who encode fine phonetic detail are not able to use this detail in early word learning tasks due to high demands, the fact that cochlear implant users may encode using coarse rather than fine phonetic details in early word representations may have significant implications. The hypothesis that the high demands of word learning may make children with normal hearing unable to focus on fine phonetic details implies that word learning requires an enormous amount of mental resources. As mentioned in the previous chapter, results on auditory processing in children with hearing impairment have shown that these children already require more effort to discriminate and process acoustic signals. The addition of semantic information in word learning may completely exhaust their mental capacities making it difficult for them to incorporate fine phonetic details when mapping word representations onto objects, even at older ages than for children with normal hearing. The fact that preparing a child for word learning in these word-object mapping tasks can be facilitative does provide hope for cochlear implant users. If children are able to use other cues such as pragmatic and syntactic information, rather than only linguistic cues, for word mapping, cochlear implant users may able to still learn to map new words to new objects. However, if cochlear implant users are delayed in their pragmatic and syntactic knowledge, which is a possibility due to decreased language exposure, they may not be possess the knowledge necessary to use such cues in word learning. We do not know exactly how much knowledge cochlear implant users have or if they acquire such knowledge at the same rate as in typically developing children. If cochlear implant users have more knowledge than typically developing children because of their more developed cognitive systems, they may be able to rely on language knowledge rather than the auditory signal for mapping words onto objects. If cochlear implant users are delayed in acquiring language knowledge in addition to being less proficient at discriminating linguistic information, they may be unable to use either method for mapping novel words to objects.

Children with Hearing Impairment

To determine what effects lexical characteristics have on word recognition performance in cochlear implant users, Kirk, Pisoni, and Osberger (1995) created the *Lexical Neighborhood Test* (LNT), "easy" and "hard" version, and the *Multisyllabic Lexical Neighborhood Test* (MLNT), "easy" and "hard" version, using Logan's (1992) corpus of words used by children aged 3-5. The easy versions consisted of high frequency words with few neighbors while the hard versions consisted of low frequency words with many neighbors. The LNT and MLNT require children to imitate and reproduce words presented in isolation.

Nineteen pediatric cochlear implant users were tested using the LNT easy and hard versions and the MLNT easy and hard lists. Word recognition for cochlear implant users was significantly better on the easy than hard word list for both the LNT and the MLNT, but that performance on the two versions did not differ when analyzed by percent of phonemes correct. Cochlear implant users with the lowest scores (near 0% range) had approximately 4 more years of auditory deprivation than users with higher scores. Results also indicated that word recognition was higher on the MLNT than on the LNT on both the easy and hard version (Kirk et al., 1995).

To extend these findings, the lexical selection process used by cochlear implant users was analyzed by measuring lexical discrimination as well as outcomes over time for “stars” and “low performers” using the LNT and MLNT (Pisoni, Clearly, Geers, & Tobey, 1999). Data analysis revealed that the “stars” consistently scored higher on both the LNT and MLNT than the “low performers”. The differences were present across all 6 years of implant use, but the largest differences between the two groups were in the first 3 years post implantation. This suggests that the “low performers” made gains with increased length of implant use, but they never reached the same level of performance as the “stars”. The “low performers” were close to floor performance on the LNT and MLNT while the “stars” scored moderately well, though they never reached the ceiling level even after six years of implant use. Children with normal hearing typically display high levels of performance on both the LNT and the MLNT by 4 years of age (Kluck, Pisoni, & Kirk, 1997). Even after 6 years of implant use, the best performing cochlear implant users were still performing at a level below that of typically developing children. This result indicates a significant lag in word recognition ability and that following a period of auditory deprivation, no matter how short, cochlear implant users may never perform at age appropriate levels, even if they use similar processes as children with normal hearing.

Findings suggest that cochlear implant users use lexical knowledge in word recognition tasks and that they recognize words in context of other words present in their lexicon, as typically developing children do. Cochlear implant users organize words in long-term memory into similarity neighborhoods and use this structural information in recognizing isolated words. The amount of phonetically similar words stored in the lexicon and word frequency affect word recognition. This notion is reflective of activation-competition models of word recognition such as NAM (Luce & Pisoni, 1998).

Data analysis also revealed a "word length effect", meaning the length of a word correlated with word recognition abilities. Word recognition was better for longer words than short words in the "stars" group. This effect was absent for the "low performers". This suggests that "stars" recognize words "relationally" in the context of other words contained in their lexicon (Pisoni et al., 1999). If they were recognizing words in isolation, either holistically or segmentally, without reference to stored representations, performance should be worse for longer than short words because longer words have more stimulus information (Luce & Pisoni, 1998). These results are consistent with findings from normal hearing children (Kirk et al., 1995; Kluck, Pisoni &, Kirk 1997; Luce & Pisoni, 1998). Longer words are easier to recognize because they are phonologically more distinct. This evidences that "stars" recognized words based on their knowledge of other words using processing strategies similar to those used by typically developing children. This also suggests that children with normal hearing and cochlear implant users share a common underlying set of linguistic processes used in recognizing spoken words in isolation (Pisoni, 2008).

These results suggest that cochlear implant users are sensitive to acoustic-phonetic similarities among words and use word length cues in recognizing words. Additionally it has been hypothesized that phoneme recognition does not reflect the perceptual processes used in spoken word recognition (Kirk et al., 1995). This is an important consideration because cochlear implant users that have relatively few words present in their lexicon may not have the vocabulary necessary to select the correct word in a word recognition task. Also, users that still have trouble detecting acoustic-phonetic differences between words may not be able to use these cues in narrowing down the possible options to select the correct word. Evidence of a word length effect is of particular importance because it reflects that some, but not all; cochlear implant users may develop a word recognition process similar to that of typically developing children. Even increased length of cochlear implant use may not resolve these differences in children that are considered "low performers".

Taken together, this research suggests that lexical characteristics such as neighborhood density and frequency may affect cochlear implant users' abilities to recognize words. In addition to this, variability exists within this clinical population that may be accounted for by factors other than length of auditory deprivation or device use. These factors studied further in order to improve the adequate therapy services provided for children with hearing loss. This is an important consideration for future research because, as mentioned before, little research has been conducted examining variables affecting cochlear implant users' outcomes other than age of implantation and length of auditory deprivation.

Spoken word recognition abilities in cochlear implant were assessed in 26 cochlear implant users with severe/profound bilateral sensorineural hearing loss, implanted prior to 29 months of age (Grieco-Calub, Saffran, & Litovsky, 2009). Cochlear implant users were assessed at 15 and 26 months post activation. Children were seated in a caregiver's lap inside of a sound booth and pictures were presented on a video screen while the labels for the objects were played from a recording. Pictures of four objects (dog, baby, ball, and shoe) were presented along with the labels for the objects and three carrier phrases ("Look at the", "Where is the", and "Can you find it?"). Two pictures were used for each object and trials were conducted in either quiet or with speech competition. Eye movements were analyzed for reaction time and accuracy. Cochlear implant users' reaction times were compared to "hearing matched" peers from the literature.

Findings revealed that the average eye gaze shift towards target was faster for normal hearing controls compared to cochlear implant users in the quiet setting. The presence of speech competitors reduced performance for both children with normal hearing and cochlear implant users. Cochlear implant users were significantly less accurate in both conditions than the control group. The group of cochlear implant users demonstrated a wide range of word recognition accuracy with some cochlear implant users performing similarly to the control group. The normal hearing control group reacted faster in the quiet setting than in the speech competition setting. The cochlear implant users reacted faster in the quiet setting; however, the difference between reaction times in quiet and speech competition was not statistically significant. The cochlear implant users were significantly slower in quiet than the control group; however, during speech competition reaction times for children with normal hearing and cochlear implant users were not significantly different.

Results also revealed that auditory experience did not correlate with reaction time. There was no significant improvement in reaction time between 15 and 26 months in the cochlear implant users, as is true for normal hearing children, based on comparison from the literature. Significant correlation was found between productive vocabulary and word-recognition accuracy in the quiet setting as well as for "hearing age" in cochlear implant users. Overall, these results suggest that cochlear implant users are slower and less accurate in identifying target objects after hearing the auditory label than normal hearing children are although some cochlear implant users were able to perform at the level of their age-matched normal hearing peers. This may be due to difficulty processing and encoding the acoustic signal or deficits in working memory capacity. Additionally, these results suggest that earlier implantation may facilitate word-learning and vocabulary development in cochlear implant users and that implantation at an earlier age may allow cochlear implant users to develop language abilities comparable to children with normal hearing.

The effects of implantation on early-word learning skills were further assessed in a group of cochlear implant users implanted between the ages of 13 and 24 months (Houston & Miyamoto, 2010). Participants were divided into two groups: users implanted between 7 and 13 months and those implanted between 16 and 23 months of age. Speech perception was assessed using 2 closed-set word recognition tasks-the *Grammatical Analysis of Elicited Language Pre-Sentence Level* (GAEL-P; Moog, Kozak, & Geers, 1983) and the *Pediatric Speech Intelligibility Test* (PSI; Jerger & Jerger, 1984), and an open-set word recognition task-the *Lexical Neighborhood Test* (LNT; Kirk et al., 1995). In the closed-set word recognition tests, the examiner presents children with four objects (GAEL-P) or six pictures (PSI) at a time, and the child is asked to point at the object or picture corresponding to the word. Vocabulary was assessed using the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007). In this PPVT, children are presented one at a time with cards containing four drawings. The examiner speaks the word corresponding to one of the drawings, and the child is required to point to it on the card. Items increase in difficulty with each subsequent group of cards.

Outcome measures were assessed at 2 intervals following implantation. The GAEL-P, PSI and PPVT were administered after 2 to 2.5 years of CI experience (first outcome interval). The LNT and PPVT were administered to cochlear implant users after 3 to 4 years of implant use (second outcome interval). In the first outcome interval, there were no significant differences on measures of speech perception between the two groups. However, the earlier implanted children performed significantly better on the measures of vocabulary than the later implanted children. The same pattern of results was found for the second outcome interval as well. This suggests that early implantation may affect the ability to learn associations between sound patterns of words and their referents. If linguistic development is based on early sensory experiences, early deprivation may have long-lasting effects on language acquisition in cochlear implant users (Houston & Miyamoto, 2010). Results indicate that auditory experience before 1 year of age may be important for developing normal word-learning skills. Not all cochlear implant users are implanted at such early ages. If the first year of life is a sensitive period for the development of word-learning skills, infants implanted after the first year of life may not develop such skills normally or to the degree that children with normal hearing or early implanted users do. Additionally, auditory deprivation in the first

2 years of life effects vocabulary acquisition. Infants experiencing increased periods of auditory deprivation may have smaller lexicons and have more trouble building a robust vocabulary compared to children implanted earlier or those with normal hearing.

Using the *Intermodal Preferential Looking Paradigm* (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987), cochlear implant users (12 to 18 months after cochlear implantation) implanted prior to 2 years of age and children with normal hearing and were tested for their ability to learn two novel word-object pairings (Houston, Stewart, Moberly, Hollich, & Miyamoto, 2012). Controls were matched by hearing age (23 12-month-olds, 23 15-montholds, 25 18-month-olds, and 28 21-month-olds) with the addition of 25 age-matched controls. Word learning was tested at either 12 or 18 months post-implantation. Stimuli for the word-learning task included two non-words, blick and modi, paired with a novel object. The visual stimuli were displayed as left and right picture-in-picture (PIP) displays on the TV monitor at the infants' eye level. Auditory stimuli were presented through speakers on the left and right of the TV monitor. Children were presented with training videos to learn two novel object-word associations. Following training, they were presented with four blocks of four test trials. Each block consisted of two trials of blick in carrier sentences and two trials of modi in carrier sentences. Between each block of test trials, children were presented with two reminder trials in which each novel word-object pair was reintroduced. If children are able to learn the associations between the visual and auditory stimuli, they should show longer looking times to the target than to the non-target during test trials.

12- and 15-month-old children with normal hearing did not look significantly longer to the target versus the non-target. Differences in looking time approached statistical significance in 18-month-olds and were significant in 21-month-olds. Children whose cochlear implants were switched on by 14 months of age or who had more residual hearing prior to implantation demonstrated word-learning in this task while later implanted infants with less residual hearing did not. This finding indicates that word-learning abilities may be related to the amount of early auditory experience in cochlear implant users.

It is possible that the age-at-implantation effect was really just an age effect since children were tested at the same post-implantation intervals rather than at the same chronological ages. Later implanted children failed may have failed at the task because the stimuli and testing procedures may not have been sufficiently engaging. To further investigate this, twenty children with similar degrees of hearing loss were divided based on their implantation age and compared to age-matched children with normal hearing (Houston et al., 2012). Data analysis showed that the early implanted group performed significantly better on the word-learning task than late implanted group. Differences in looking time between the target and non-target were statistically significant for the early implanted group and their age-matched peers as well as for the age-matched peers of the later implanted group. There was no significant difference in looking time for the later implanted group. This suggests that the inability to learn words in the later implanted group was due to age of implantation.

Additionally, only the 18- and 21-month-olds with normal hearing showed evidence of word learning while the hearing age of the cochlear implant users ranged from 10 to 20 months of age. It is possible that children implanted by 1 year of age may have superior word-learning skills compared to their hearing age-matched peers. This may be due to differences in general cognitive development. Earlier implanted infants were chronologically older than their hearing age-matched peers suggesting that differences in cognitive mechanisms such as sensory integration and working memory, rather than perceptual discrimination, may have contributed to this difference.

To examine whether early word-learning skills predict later vocabulary outcomes, performance on the word-learning task was compared to performance on several other speech and language assessments 6 months to 1 year after the word-learning test was administered (Houston et al., 2012). Speech perception was assessed using 2 closed-set word recognition tasks-the *Grammatical Analysis of Elicited Language Pre-Sentence Level* (GAEL-P; Moog, Kozak, & Geers, 1983) and the *Pediatric Speech Intelligibility Test* (PSI; Jerger & Jerger, 1984), and an open-set word recognition task-the *Lexical Neighborhood Test* (LNT; Kirk et al., 1995). The *Peabody Picture Vocabulary Test* (PPVT; Dunn & Dunn, 2007) was used to assess vocabulary in cochlear implant users. Vocabulary was assessed in age-matched children with normal hearing using the *MacArthur- Bates Communicative Developmental Index* (MCDI; Fenson, Marchman, Thal, Dale, Reznick, & Bates, 2005). The toddler form, designed for infants aged 16-30 months, assessing productive vocabulary knowledge and aspects of grammar was used with children with normal hearing.

The GAEL-P and PSI were administered two years after initial implantation. At this time, cochlear implant users were between the ages of 2.5 and 4. The LNT was administered four years after implantation. At this time, cochlear implant users were between the ages of 4.5 and 6. The PPVT: IV was administered at both post-implantation intervals. The MCDI was administered to NH children at the time of testing in the word-learning experiment. Vocabulary and closed-set word recognition tests were administered to the cochlear implant users two years after implantation (6 to 12 months following the word-learning tests). Vocabulary and open-set word recognition tests were administered four years after implantation. Vocabulary measures for age-matched children with normal hearing were all collected at the time of word-learning testing.

Correlations between looking time and scores on the speech and language tests were examined. Performance on the word-learning task was related to later measures of vocabulary size. Word-learning performance correlated significantly with the measure of vocabulary size (PPVT) at two years post-implantation. The relationship between word-learning performance and vocabulary four years post-implantation approached statistical significance. Correlations with measures of speech perception were all positive, but were not statistically significant (Houston et al., 2012).

Taken together, the findings from Houston and Miyamoto (2010) and Houston and colleagues (2012) indicate that there may be a sensitive period for accessing sound that is important for development of word-learning abilities. Earlier access to sound may lead to better speech perception skills. If infants are unable to discriminate sound patters of words, word learning will be difficult. However, the fact that there was no significant correlation between the ability to learn words and speech perception measures (Houston et al., 2012) indicates that this is unlikely. An additional hypothesis is that earlier access to sound may allow infants to develop other cognitive mechanisms such as sensory integration, which has been shown to play a role in word learning (Gogate & Bahrick, 1998). Working memory may also be affected by early auditory experience. Phonological working memory has been linked to early stages of vocabulary acquisition in typically developing children (Baddeley, Gathercole, & Papagno, 1998). Research investigating working memory in cochlear implant users has revealed similar findings (Pisoni & Cleary, 2003).

The ability to learn words after only a few exposures has been shown to be an important component of language development (e.g. Carey, 1978; Carey & Bartlett, 1978; Heibeck & Markman, 1987; Markson & Bloom, 1997). Word-learning skills were assessed in 24 cochlear implant users between the ages of 2 and 6 with at least 1 year of implant use were divided into two groups: young (2-3 years of age) and old (4-5 years of age) (Houston, Carter, Pisoni, Kirk, & Ying, 2005). Cochlear implant users were paired with age-matched controls. Stimuli consisted of 16 Beanie Baby stuffed animals. Animals were selected on the basis of having distinctive features that could be easily named (i.e. bright color or big ears). Beanie Babies were renamed based on one of their attributes and grouped into four sets so that the attribute names could describe at least two of the animals in the set (i.e. at least two were red or had wings). Young infants were exposed to one set of four Beanie Babies, while older infants were exposed to two sets.

Beanie Babies were presented during a play scenario. The name of the Beanie Baby was produced 8 times in the scenario and the infants produced the name 3 times.

To assess name learning, a receptive and an expressive test were given to the infants following training. The receptive test used a forced-choice identification task and the expressive test used a cued-recall task. In the receptive test, the entire set of Beanie Babies was placed in front of the child along with a bus or a truck. The infants were asked to put a specific Beanie Baby into the truck or bus. The expressive test was conducted using a "knock knock" game. A Beanie Baby was placed behind a toy and an experiment would say "Knock Knock. Who's there?" The child was asked to name the Beanie Baby that was hidden behind the toy. This was repeated for each Beanie Baby in the set. This training and testing procedure was used again with a second set of Beanie Babies.

The mean performance of cochlear implant users was significantly lower on both receptive and expressive tests of word learning than the mean performance of children with typical hearing. Additionally, the group of cochlear implant users demonstrated a greater range of performance on the receptive tests than children with normal hearing. These findings are consistent with previous studies finding that although language skills improve following cochlear implantation, cochlear implant users generally do not perform at the same level as age-matched peers with normal hearing (e.g., Kirk et al., 1995; Pisoni et al., 1999; Pisoni & Clearly, 2003).

Word learning reflects a child’s ability to quickly encode phonological information into long-term memory and make links to referents (Houston & Miyamoto, 2010). Previous research has found that cochlear implant users have an atypical working memory capacity (Pisoni & Cleary, 2003) and have argued that a limited working memory capacity may reflect an inability to use verbal rehearsal procedures and maintain phonological information in working memory (Burkholder & Pisoni, 2003; Pisoni & Clearly, 2003). To test this, children were given the same receptive and expressive tests from both set 1 and set 2 following a 2 hour delay to assess long-term memory of the learned names. The first analyses of the data suggested that performance on the delayed tests did not differ significantly from the mean performance on the immediate tests for either group of children. However, when known and unknown words were separated out, there was a weak but statistically significant main effect of delay on cochlear implant users’ ability to learn words. This suggests that some of the differences in word-learning may reflect general language abilities such as vocabulary development in addition to differences in hearing. In this study, participants were matched based on chronological age and no testing to assess language abilities, such as vocabulary measures or receptive and expressive language skills, was conducted. Conducting a similar study in which cochlear implant users are matched to controls with similar receptive and expressive language skills and vocabulary sizes may provide additional information on the effects of global language ability on word learning. This would help us to determine how much differences in word-learning abilities may be affected by differences in hearing status versus general language abilities.

Both children with normal hearing and cochlear implant users performed significantly better on the receptive word-learning tests than on the expressive tests in the immediate and the delay condition. Cochlear implant users showed larger differences in performance between receptive and expressive tests than the children with normal hearing. In both receptive and expressive tasks, children must encode the names into memory and learn to associate them with the correct object. In receptive tests, representations of the correct word can be accessed from memory more easily because the experiment provides retrieval cues and context (i.e. providing the name of the Beanie Baby to be selected). In the expressive test, the child had to have representations robust enough to retrieve the name from memory without any retrieval cues being provided (Houston et al., 2005). In other words, expressive tasks require the child to generate the correct name while the receptive test required only recall of the representation. Previous research on speech feature discrimination abilities in word recognition tasks have indicated that cochlear implant users may encode using "coarse" or "underspecified" phonological representations (Pisoni et al., 1999). If the representations of the words cochlear implant users formed contain less fine-grained acoustic-phonetic detail and were not phonologically well specified it may have caused the names to be difficult to access in the expressive test.

DISCUSSION AND CONCLUSIONS

Research on word learning in children with normal hearing shows that children may be unable to use fine phonetic detail in word learning tasks because of high cognitive demands. If cochlear implant users already require more processing capacities to discriminate and process auditory information or are unable to encode phonetic detail in early lexical representations, the additional load of attaching semantic information to novel words may cause them to be unable to learn novel word-object pairings. This has been partially evidenced in studies assessing cochlear implant users' abilities to pair novel objects with words, even when they are able to perceive differences in speech sounds (Houston & Miyamoto, 2010; Houston et al., 2012).

Research has also indicated that cochlear implant users use lexical knowledge in word recognition tasks and recognize words in context of other words present in their lexicon, as typically developing children do (Kirk et al., 1995; Pisoni et al., 1999) and that phonetic similarity between words effects cochlear implant users' ability to recognize words. This is an important finding because with decreased language exposure, children with hearing impairment may have fewer words in their lexicon to select from as well as less exemplars of the words in their lexicon. Conducting research assessing the effects of indexical properties, such as talker variability, in cochlear implant users may provide information to help us determine if reduced language exposure or less variation in examples for words affects cochlear implant users' ability to recall words in word recognition tasks.

The finding that word length had an effect on the ability to recognize words is particularly important because it suggests that cochlear implant users recognize words using processing strategies similar to those used by typically developing children. If the processes used in word recognition are similar for children with normal hearing and those with cochlear implants, differences in word recognition abilities and phonological lexical development must be attributable to some other factor. Again, the fact that there was intergroup variability suggests that factors other than lexical characteristics and length of auditory deprivation impact the language development of cochlear implant users.

The ability to maintain words in working memory has been shown to facilitate transfer and encoding of representations into long-term memory in both children with typical hearing (Baddeley et al., 1998) and in cochlear implant users (Cleary, Pisoni, & Kirk, 2002). Phonological working memory is a strong predictor of vocabulary knowledge (Gathercole & Baddeley, 1990) and of long-term learning of new sound patterns in children with normal hearing (Baddeley, Gathercole, & Papagno, 1998). If cochlear implant users have a more limited working memory, they may have difficulty encoding newly learned words into long-term memory.

Research on children with normal hearing have also showed that preparing a child for word-learning by clarifying referential status can be facilitative (Fennell & Waxman, 2010). If cochlear implant users acquire semantic and syntactic knowledge, possibly more rapidly due to more developed cognitive systems, they may be able to use general language knowledge in addition to acoustic information in learning to association novel words and objects. If cochlear implant users are delayed in acquiring language knowledge in addition to being less proficient at discriminating linguistic information, they may be unable to use either method for mapping novel words to objects. Research on receptive and expressive language abilities of cochlear implant users comparing them to both age- and hearing-matched peers could provide information on how much knowledge cochlear implant users have. Longitudinal studies comparing cochlear implant users to age- and hearing-matched peers on general language abilities may help us determine if earlier implanted users acquire language knowledge at a rate comparable to typically developing children.

Overall, research on word-learning suggests that children with normal hearing and those with hearing impairment may differ in the processes used to encode sensory information and the amount of detail encoded in early lexical representations as well as cognitive processing capacities, such as working-memory, that are used for later word learning and lexical development (Pisoni et al., 1999). Literature has shown that even after years of cochlear implant use, hearing impaired children may still lag in word recognition abilities, both of which contribute to speech and language functioning and the building of a robust mental lexicon (Briscoe, Bishop, & Norbury, 2001; Pisoni, Clearly, Geers, & Tobey, 1999; Pisoni & Clearly, 2003). It has been shown that the brain and nervous system are able to develop even in the absence of auditory stimulation; however, recent evidence suggests that cortical reorganization takes place during a period of sensory deprivation before cochlear implantation leading to atypical development of speech and language skills (Pisoni, 2008). Variability in language outcomes following implantation may be a result of peripheral and central differences in neural functioning (Pisoni, 2008) in addition to length of auditory deprivation (Harrison et al., 2005). Now that studies assessing auditory processing, sound discrimination, phonological development and word recognition in children with normal hearing and children with hearing impairment have been discussed, as well as intergroup variability, we can begin to draw conclusions about the correlations between these various processes and use those conclusions to make sure we structure therapy to address the specific needs of this clinical population.

Chapter 6: General Discussion and Conclusions

Research on auditory processing, sound discrimination, phonological development and word recognition has shown that there are significant differences between children with cochlear implants and children with normal hearing. In addition, there is also great variation within this clinical population as might be expected since there is normal variation in typically developing children as well, especially since the type and degree of loss and age of correction varies so greatly. How can we use the knowledge we have gained from this research to ensure better outcomes for cochlear implant users? What do we still need to learn more about?

AUDITORY PROCESSING

Studies assessing automatic processing in children with hearing impairment reveal that this clinical population may already require more cognitive capacities in processing the acoustic signal and that auditory information may not be processed as automatically as in typically developing children (Garner, 1974a; Garner, 1974b; Jerger et al., 1995; Jerger et al., 1997). Effortful processing of the acoustic signal leaves less mental capacities available for the integration of auditory information into memory (Reed, 2007). This supports the idea that the ability to process acoustic information is affected by access to auditory cues as well as the availability of capacities for integration and storage of auditory information. Evidence has also shown that children receiving their cochlear implants at later ages may have difficulty pairing auditory and visual events. Though it is unclear if the later implanted infants detected the intersensory redundancy, if failure on the task was due to inability to encode the redundancy it may be further evidence that processing an auditory signal requires the allocation of so many mental resources in cochlear implant users that they have few processing resources left over for other things. These results again suggest that high processing demands of attending to the acoustic signal may cause cochlear implant users to struggle in more difficult speech related tasks, such as speech in noise perception, spoken word recognition, and word learning. This ability is not required for word learning, but a study on older cochlear implant users showed that presenting stimuli in a combined condition (auditory and visual) resulted in better language comprehension scores.

ATTENTION TO SPEECH

Research on cochlear implant users' attention to speech has shown that although they pay increasingly more attention to sound following implantation, sound still does not capture their attention to the degree it does in typically developing children (Houston, Pisoni et al., 2003). Children with normal hearing begin paying attention to speech directly after birth, providing them with language learning opportunities from the earliest stages of development. Infants are able to discriminate between different sounds from birth, and in the second half of their first year of life learn to attend only to those sound contrasts which are important in their ambient language (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Werker & Tees, 1984). If cochlear implant users are not paying as much attention to speech as children with normal hearing following implantation they may still be missing out on some of the opportunities typically developing children have from birth on. This may have severe implications for the development of speech discrimination and word recognition abilities in these infants. Not all children receiving cochlear implants are implanted at early ages. Some children are not implanted until late childhood, although these decisions are very typically made early in contemporary practice. Children implanted at later ages may miss a crucial point in time that would allow them to develop like a normal hearing infant. Attention to speech may also affect infants' ability to map novel words to objects which is an important part of word learning (Werker et al., 2002).

It may be that differences in attention to speech are a result of differences in chronological age between cochlear implant users and children with normal hearing. Studies assessing attention to speech in cochlear implant users all used hearing age-matched controls. Comparing cochlear implant users to peers matched based on hearing experience seems like it would make sense since children who have only been hearing for a few months cannot be expected to process auditory information as efficiently as children who have been hearing for a few years. However, matching by hearing age does not control for additional developmental differences. Cochlear implant users are chronologically older and more cognitively developed than their hearing age-matched peers. It may be that the stimuli or procedure used in these studies did not capture cochlear implant users' attention because of differences in cognition. To determine whether differences in attention to sound are due to delay in access to sound, it would be optimal to conduct research on how chronologically matched children with normal hearing perform in this same task. If they also show reduced attention to sound, it would indicate that differences between cochlear implant users and their hearing age-matched peers may be due to differences in cognition and interest in the task itself. If this is the case, additional methods that would better captivate older infants' attention will need to be developed to determine whether cochlear implant users really do pay less attention to speech than children with normal hearing. If research on chronologically age matched children with normal hearing indicated that cochlear implant users reduced attention to sound is not due to differences in cognition, it could be due to differences in perception of the signal. The acoustic signal perceived by cochlear implant users may be less interesting to them because it is not as intense as the sound heard through a normal cochlea. Additional research using more robust or interesting stimuli may help us to determine if differences in perception of the signal cause this apparent reduction in attention to speech.

SPEECH DISCRIMINATION

Studies assessing the ability to process acoustic information indicate that children with hearing impairment are not as proficient in detecting differences in the acoustic signal as those with normal hearing (Boothroyd, 1984; Horn, Houston, & Miyamoto, 2007; Johnson, Whalley, & Dorman, 1984; Pisoni et al., 1997, Pisoni et al., 1999). Sound discrimination studies on infants with normal hearing show that they perceive consonants categorically (Eimas et al., 1971; Maye et al., 2002) and can detect variations in suprasegmental aspects (i.e. frequency, intensity, VOT). Children with hearing impairment are not as sensitive to phonetic contrasts as children with normal hearing. Research on children with hearing impairment has indicated a decreased ability to discriminate temporal and frequency cues, such as VOT, for determining differences in voicing, manner, and place of articulation suggesting that unlike children with normal hearing, children with hearing impairment do not perceive consonants categorically.

Speech feature discrimination studies (Pisoni et al., 1997; Pisoni et al., 1999) show that even the most proficient cochlear implant users are still unable to process contrasts adequately. Though discrimination abilities improve over time, cochlear implant users are still significantly impaired in this area compared to typically developing peers. Cochlear implant users falling in the lower performance range struggle greatly with speech feature discrimination even after 6 years of implant use. Based on this evidence, it is possible that cochlear implant users may have difficulties discriminating between speech sounds that are highly phonetically similar and vary by only one feature (place, manner, or voicing).

One possible explanation is that cochlear implant users pay less attention to speech and therefore take longer to become sensitive to speech contrasts such as place, manner, and voicing. Further research on the reasons for the apparent decreased attention to speech may help us to determine if difficulties in phonetic discrimination are related to differences in auditory processing and attention or decreased access to the auditory signal. Additionally it may be beneficial to conduct research looking at how different phonemes must be from each other for cochlear implant users to reliably discriminate between them. This could be done by assessing whether cochlear implant users discriminate between phonemes that vary by two or three features such as /t/ and /k/ (place and voicing) or /s/ and /g/ (place, manner, and voicing). The results from Pisoni and colleagues (1999) showed that cochlear implant users do not perform as well as typically developing peers on speech feature discrimination tasks; however, these peers were matched based on chronological, not hearing age. Repeating the study and comparing cochlear implant users' abilities directly to hearing age-matched peers would allow us to see if cochlear implant users develop discrimination abilities at a rate comparable to children with normal hearing.

Another point to note is that in the study by Pisoni and colleagues (1999), speech feature discrimination abilities were tested within the context of word recognition. It is possible that the added task of having to recognize words made it difficult for cochlear implant users to use fine phonetic detail. Research on younger children with normal hearing has shown that even if they can perceive different contrasts in discrimination tasks they may not be able to in word learning tasks due to high task demands (Fennell & Waxman, 2010; Werker et al., 2002). Conducting a similar speech discrimination study in which task demands were lower would provide evidence on how well older cochlear implant users are able to discriminate consonant contrasts at the simplest level: isolation. If they cannot reliably discriminate, even at the isolated phoneme level, therapy may need to incorporate aspects of auditory training to increase cochlear implant users' ability to discriminate between similar phonemes. Without the ability to detect fine phonetic differences, cochlear implant users may miss out on word learning opportunities when they are unable to hear minimal differences between words. Furthermore, children with normal hearing use allophonic cues to help them segment words from fluent speech. Decreased sensitivity to small phonetic changes may make it more difficult for cochlear implant users to detect such differences.

Speech Segmentation

In order to learn words, infants must recognize where words begin and where they end. Isolated words are processed less efficiently than words within phrases (Fernald & Hurtado, 2006). Children with normal hearing are sensitive to transitional probabilities (Johnson & Jusczyk, 2001; Saffran, Aslin, & Newport, 1996; Thiessen & Saffran, 2003), differences in stress and prosody (Jusczyk, Cutler, & Redanz, 1993; Jusczyk, Houston, & Newsome, 1999; Nazzi, Dilley, & Jusczyk, 2003), and variations of phonemes (allophones) (Jusczyk, Hohne, & Bauman, 1999; Mattys & Jusczyk, 2001) and can use these to segment individual words from fluent speech. Word recognition requires the identification of sequences and phonetic detail from the speech signal (Eisenberg, 2007) suggesting that deficits in attention to sound, auditory processing, and speech feature discrimination may negatively impact the ability to segment words and learn where word boundaries are. The developing ability of children with hearing impairment to segment speech is an area in which research is lacking. Research determining if, and when, cochlear implant users are able to use these various aspects of speech to segment words is needed. Insight into how this ability develops in cochlear implant users and which cues they are most responsive to is an important area of future research. Additionally, little research has been conducted on chronologically older children with normal hearing in this area. We need to know if older children are still as sensitive or attentive to speech patterns as younger children with normal hearing. It may be that children with normal hearing in a sense "lose" their ability to segment words based on phonetic patterns because they are more cognitively advanced. Comparison to chronologically age matched peers would allow us to control for general age related changes that may affect speech segmentation abilities.

New studies should match cochlear implant users to controls based both on hearing age and chronological age. This would ensure that differences in auditory experience and language exposure as well as cognitive development and age related changes are controlled for. It is possible that because cochlear implant users are chronologically older, they may be able to detect rhythmic patterns in their ambient language sooner and develop segmentation abilities more rapidly after implantation than children with normal hearing. On the other hand, prolonged periods of auditory deprivation and difficulty discriminating between speech sounds may cause cochlear implant users longer to develop segmentation abilities. Difficulty perceiving allophonic variations because of poor auditory input and processing may cause cochlear implant users to have difficulty correctly segmenting individual words. As mentioned previously, decreased attention to speech may also cause cochlear implant users to take longer to develop segmentation abilities. If cochlear implant users pay less attention to speech, they may be less perceptive or less interested in rhythmic and prosodic patterns in fluent speech. New research on attention to speech as well as research on segmentation abilities in older children with normal hearing would allow us to rule this out as a possibility for any differences in rate of segmentation ability.

Word Recognition

Results from Pisoni and colleagues (1999) indicate that cochlear implant users do not encode as much fine phonetic detail in lexical representations, even at older ages, and that high neighborhood density between words affects cochlear implant users' ability to recognize words (Luce & Pisoni, 1998). This may have a significant impact given the hypothesis that word recognition is based on activation and competition between similar lexical representations in memory and the assumption that high density words are more difficult to accurately retrieve accurately because of increased competition.

Decreased language exposure may result in cochlear implant users having less experience with variable productions of the same word as well as fewer total words in their lexicon. This may pose a problem since studies investigating speaker variability suggest that indexical properties, such as talker variability, might affect infants' ability to generalize lexical representations to new contexts (Houston, 1999; Houston & Jusczyk, 2003). Exposure to multiple exemplars of new words may facilitate word recall in infants and help make early representations more robust. If decreased exposure causes cochlear implant users to perceive similar productions of the same word as different words, they may have trouble extracting words from memory if the form heard does not exactly match the stored form. This could cause difficulty generalizing learned words to different contexts and may cause them to "overspecify" stored representations.

It would be beneficial to conduct a study assessing the effects of talker variability or variation in production on cochlear implant users' ability to recall and recognize words. A study assessing the perceptual magnet effect in cochlear implant users would help us to determine if cochlear implant users also categorize phonemes based on prototypical productions. Results could then be compared to hearing-age matched peers since the study conducted by Kuhl (1991) assessed adults in addition to infants and found that they responded similarly. Also studies assessing word recognition based on different talkers, such as the ones conducted by Houston (1999) and Houston and Jusczyk, (2003), comparing cochlear implant users to hearing matched peers should be done. This would give us insight into whether or not indexical properties affect cochlear implant users in the same way that they do children with normal hearing. If cochlear implant users also have difficulty recognizing variable productions of words, it would be beneficial to integrate this into therapy. Therapy could involve exposing cochlear implant users to multiple productions of the same word that vary based on things such as talker gender to facilitate generalization of lexical representations to different contexts.

Also, evidence has shown that cochlear implant users recognize words based on other words in their lexicon. However, if cochlear implant users have relatively few words in their lexicon, they have fewer words to choose from in selecting a correct lexical representation and to compare words to in order to encode presentations as “new” words or variations of an already stored representation. One could argue that in this case, cochlear implant users would perform similarly to younger children with normal hearing that have smaller lexicons. Research assessing word recognition and word learning has only matched cochlear implant users to children with normal hearing of the same chronological age or hearing age. Matching cochlear implants based on chronological age does not control for the fact that cochlear implant users may have 2 to 3 less years of speech and language exposure. Matching cochlear implant users based on hearing age does not necessarily mean that the cochlear implant users and the controls will have similar language levels. Cochlear implant users cannot be expected to perform similarly to either group of controls since there is normal variation even in children with normal hearing of the same chronological age. To determine if cochlear implant users do in fact perform similarly to children with smaller lexicons, studies on word recognition and word learning would have to match participants based on language and vocabulary size.

Working Memory

If recognizing words with high neighborhood density requires additional mental capacities, as Luce and Pisoni (1998) argue, cochlear implant users may be at an even greater disadvantage and be unable to discriminate or integrate the phonetic details that they are able to perceive into memory for later use in word learning. Working memory data has shown that cochlear implant users differ in their short-term working memory capacities from typically developing children. Results from forward digit span tasks suggest a difference in processing strategies used to maintain verbal information in short-term memory (Pisoni & Clearly, 2003) and that longer digit spans have been correlated with better performance on word recognition tasks. If forward digit spans are indeed reflective of strategies used to maintain information within short-term memory, differences in memory capacity could help explain the variation in later language outcomes for cochlear implant users, regardless of their amount of language exposure and experience. If attention and executive functioning abilities as well as coding strategies and verbal rehearsal are related to word recognition outcomes, continued research in these areas to determine exactly what causes these differences and how they might best be remediated is crucial. As mentioned previously, digit span, speech rate and interword pause time are reflections of verbal working memory, not general working memory. It is likely that cochlear implant users have adequate working memory capacities and that it is the addition of verbal information that affects their performance on working memory tasks. A study should be conducted comparing cochlear implant users' performance on the WISC-III digit span task to a digit span task that requires them to write down the numbers or answer in a way that does not require verbal production. If performance on both is equally poor, it would be a suggestion that cochlear implant users truly do differ in working memory capacity. However, if cochlear implant users performed better on the non-verbal task it would suggest that the addition of verbal information hindered their ability to store information in working memory. This would indicate that working memory deficits are related to the amount of effort needed to process the acoustic signal. Furthermore, comparing verbal working memory scores to infants that are matched by hearing-age would allow us to determine if verbal working memory develops more slowly in cochlear implant users following access to the acoustic signal or if differences between cochlear implant users and age-matched peers is a reflection of decreased working memory capacity.

The fact that communication mode (oral versus total communication) impacts the ability to retain longer sequences in immediate memory indicates that coding and verbal rehearsal processes may be affected by the amount of linguistic experience a child has. This suggests that infants implanted at an earlier age may need less effort to process auditory information allowing them more mental resources for retaining information in working memory. Studies on working memory have not yet been conducted on infants implanted before the age of 1. Research on early implanted children's working memory capacity would allow us to compare the development of working memory ability based on hearing experience within the cochlear implant population. Studies assessing earliest implanted children should also focus on comparing verbal working memory and general working memory differences. It is possible that infants implanted at 6 months of age do not have verbal or general working memory deficits at all due to a shorter period of auditory deprivation. This would suggest that the neural reorganization that takes place between the first 6 to 12 months of life may be the cause for working memory impairment in cochlear implant users.

Overall, working memory studies indicate that early implantation, though extremely beneficial, may not be enough on its own to ensure later language proficiency. Not only is early implantation important, but providing a cochlear implant user with sufficient language exposure that is specifically tailored towards their unique needs is an additional necessity. It may be helpful to initially focus only on basic speech feature detection and discrimination to help cochlear implant users to process auditory stimuli more efficiently. If processing verbal information confounds working memory capacity, helping cochlear implant users to process acoustic information more automatically could free up working memory capacity needed to retain phonological representations for encoding in long-term memory, It is possible that no amount of therapy will allow for cochlear implant users to process acoustic stimuli as easily as children with normal hearing do simply because the acoustic signal is not “natural” and because of possible cortical reorganization. Pilot studies assessing if such new therapy techniques did improve auditory processing and increase verbal working memory would be invaluable to our field.

LEXICAL REPRESENTATIONS AND WORD LEARNING

Studies assessing word learning abilities based on phonetic similarities show that children with normal hearing may not be able to perceive different contrasts in word learning tasks, even if they can do so in discrimination tasks. This may be due to the high computational demands of word learning (Werker et al., 2000). Evidence has shown that infants are able to use fine phonetic detail in mapping words to objects when the novel word has a clear referential status (Fennell & Waxman, 2010) based on either syntactic or pragmatic cues suggesting that only once referential status is clarified can young infants use fine phonetic detail in word-object mapping. This clarification of the referential status of words in this task sufficiently decreases the processing demands of word learning in children with normal hearing, so that they are able to attend to the phonetic details of the newly learned words. This study provides evidence that cognitive processing overload, as originally hypothesized by Werker and colleagues (2000), makes it difficult for young children to attend to phonetic detail in word learning tasks and clarifying the referential status of the word is which the cognitive processing load can be reduced.

If cochlear implant users have less semantic and syntactic knowledge, they may not be able to use linguistic and pragmatic information to infer referential status of a novel word. It is not yet clear how much language knowledge cochlear implant users possess and how long it takes them to acquire the amount of knowledge typically developing 14-month-olds have, but if there is a significant lag, cochlear implant users may have trouble inferring that a novel word is referring to a presented object. In order to determine this, research comparing cochlear implant users to hearing matched peers using the same procedure should be conducted. Additionally, a similar procedure should be used on cochlear implant users with 14 months of hearing experience should be conducted. It is possible that cochlear implant users with 14 months of hearing experience would perform similarly, or even better, in such a task as 14-month-old children with normal hearing.

Werker and colleagues (2000) hypothesized that infants are unable to use phonetic detail when the processing load of a task is too high. If infants expend the majority of their mental resources to form semantic links between the object and the phonetic pattern, they may have less mental capacities available for the encoding of fine phonetic detail. If word learning imposes such high processing demands on typically developing children who have encoded fine phonetic detail that they are unable to use this detail in such tasks, the fact that cochlear implant users representations may already contain less phonetic detail could have significant implications on word learning. If cochlear implant users already have reduced working memory capacity language processing abilities and they additionally struggle to discriminate between phonetically similar words, tasks such as word learning that require additional processing may make it extremely difficult for cochlear implant users to correctly process information, store representations, and map those representations onto actual objects or concepts. This could delay the development of vocabulary in cochlear implant users which would delay both their expressive and receptive language abilities.

In the study by Houston and colleagues (2005), a receptive and an expressive test were used to assess word learning. However, differences in receptive and expressive language ability were not assessed prior to the word-learning task. Differences in receptive and expressive skills were only analyzed in the context of the word learning task. If cochlear implant users have relatively similar levels of general receptive and expressive language abilities, worse performance on expressive abilities in word-learning tasks may be attributable to the additional processing load of having to generate rather than recall a word on top of having to encode the phonological information and map it to a referent,

It is also possible that the representations cochlear implant users formed were underspecified, as has been indicated by previous research (Pisoni et al., 1999), and the lack of detail caused cochlear implant users to have difficulty accessing and retrieving newly learned words from memory in expressive tasks. Conducting research similar to that done on 14-month-old children with normal hearing, such as Stager and Werker (1997) and Fennell and Waxman, (2010), to evaluate how much phonetic detail is contained and used in early word learning in cochlear implant users may help us to determine if discrepancies between receptive and expressive tasks are due to the amount of detail cochlear implant users encode in lexical representation and are actually able to use in word learning when task demands are reduced.

When conducting research assessing word learning in cochlear implant users as well as in children with normal hearing, general language skills should be tested prior to assessing word learning. That would allow for comparison of performance variation within the cochlear implant group based on language abilities as well as to language matched peers with normal hearing. Studies comparing intragroup variation without dividing cochlear implant users up based on age of implantation or hearing experience would allow us to determine how much of an effect language knowledge has on cochlear implant users' ability to learn words. Oppositely, dividing age-matched cochlear implant users into groups based on age of implantation and assessing intragroup variation would help us determine if there are differences in language and vocabulary based on hearing experience, and if so, how these might affect the ability to learn words.

Results indicating that cochlear implant users' performance on word-learning in a delayed condition, as in Houston and colleagues (2005), was affected by previous word knowledge (known versus unknown words) suggests that working memory or vocabulary size and general language abilities may affect the ability to learn words.

Houston and colleagues (2005) mentioned that they were unable to compare performance between immediate and delayed condition for known and unknown words for children with normal hearing because children with normal hearing were familiar with almost all of the words/names used in the study. Conducting a study similar to that done by Houston and colleagues (2005) using non-words or words that were unfamiliar to both cochlear implant users and children with normal hearing would help us to determine if unfamiliarity with the words caused the discrepancy between the immediate and the delayed testing conditions. Simply comparing cochlear implant users to hearing age-matched controls may also help alleviate the differences in prior word knowledge.

Additionally, Houston and colleagues (2005) matched cochlear implant users to controls based on chronological age. This controls for general cognitive development, but cochlear implant users have had less access to sound than same-age children with normal hearing. Therefore they cannot be expected to have similar levels of language knowledge or vocabulary size. Research comparing cochlear implant users to language and vocabulary matched peers would be beneficial in helping us determine if difficulty maintaining phonological representations in working memory is due to decreased working memory capacity or differences in general language ability. As previously discussed, research has indicated that cochlear implant users have decreased verbal working memory capacities (Pisoni & Cleary, 2003) which may be a result of the failure to use verbal rehearsal and maintain phonological information in working memory (Burkholder & Pisoni, 2003; Pisoni & Clearly, 2003). It is possible that the differences in performance between cochlear implant users and children with normal hearing were actually due to differences in size of the lexicon and language knowledge rather than the ability to quickly learn words.

Results from Houston and colleagues (2012) indicate that the ability to learn words may be affected by the amount of early auditory experience. Infants in this study were originally matched based on post-implantation intervals, rather than chronological age. To control for an age effect, the authors divided the cochlear implant users into early and late implanted groups and compared them to age-matches. Following this, it was evident that differences in word-learning ability really were attributable to implantation age.

Additionally, this study found that some cochlear implant users showed evidence of word learning earlier (based on hearing age) than some children with normal hearing that have had more hearing experience suggesting that children implanted before the first year of life may have more advanced word learning skills. The fact that early implanted infants were able to learn words with less hearing experience than children with normal hearing may be related to additional developmental factors. A more advanced cognitive system may allow cochlear implant users to begin associating words and objects sooner following implantation. The study by Houston and colleagues (2012) did not directly compare cochlear implant users to hearing matched peers so to further investigate this hypothesis, a similar study should be repeated in which cochlear implant users are divided by age of implantation and matched to hearing-matched peers.

Concluding Remarks

In summary, cochlear implant users differ in their ability to process and attend to auditory information, encode this information into their systems, and retrieve it for word learning. Cochlear implant users may also differ in the amount of detail they encode as well as the amount of mental resources they require for word learning. It is not yet certain if this is attributable to allocation of mental resources, working memory capacity, accessibility of the acoustic signal, neural restructuring following a period of auditory deprivation, or a combination of these factors. Variability in later outcomes in cochlear implant users may be a result of some of these additional factors, rather than just the length of auditory deprivation. Future research should focus on how these factors interact with each other and which of them may cause some of the deficits in language learning in cochlear implant users. Future research should also focus on how syntactic and pragmatic language knowledge as well as perceptual sensitivity affects the ability to map novel words to objects. Overall, our knowledge on the processes in language learning used by very young cochlear implant users is very limited. It can be difficult to develop testing paradigms that can be used reliably with infants so young, but it is a necessity if we are to provide proper services for this population. Research on typically developing children needs to be expanded as well. We cannot hope to describe what is “atypical” if we cannot define what “typical” looks like. Once we have a deeper understanding of the typical developmental trajectory, we will be better able to apply that knowledge in determining where cochlear implant users go off course. If differences in word recognition and lexical development are related to additional factors such as executive functioning and working memory capacity, as has been suggested based on the current research, therapy will need to focus on remediating these processing deficits in addition to increasing cochlear implant users’ abilities to discriminate and segment speech. If these additional factors are ignored, it may be like we are trying to teach cochlear implant users to run before they can even walk. We must first focus on the prerequisites to phonological development word recognition and ensure cochlear implant users have a the processing capacities necessary to have a solid basis in these areas before moving on to more advanced language abilities like lexical development.

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