THE EFFECT OF AUDITORY INPUT ON THE RATE OF SPEECH PRODUCTION BY COCHLEAR IMPLANT USERS

by

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To my husband Sean, my two children, Serena and Aaron, and to my parents.

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DISSERTATION
Presented to the Faculty of
The University of Texas at Dallas
in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY IN
COMMUNICATION SCIENCES AND DISORDERS

THE UNIVERSITY OF TEXAS AT DALLAS
May 2018

ACKNOWLEDGMENTS

First of all, I would like to acknowledge and sincerely thank Dr. William Katz, my research advisor and a wonderful mentor. Dr. Katz provided technical guidance, research expertise, and academic mentorship as well as exhibiting patience, understanding, and flexibility while advising an international student pursuing a PhD. I would also like to thank my former advisor, Dr. Emily Tobey, for providing for me the opportunity to study and research at the University of Texas at Dallas in a field that I am passionate about pursuing. I want to express my heartfelt gratitude to my committee members, Dr. Andrea Warner-Czyz, Dr. Ann Geers, and Dr. Christine Dollaghan, for their support, patience, kindness, and valuable feedback throughout this project. I would also like to thank the members of Dr. Katz's Lab: Dr. Reidy for helping my statistical analysis using R, Evi Doli and Annette Glotfelty for reading my drafts, Sonya Mehta for helping analyze data, Sishi Liu and Kelly Fazel for their helpful feedback on my project, and my former lab mates, Janet Lane, Madhu Sundarrajan, and Olga Peskova, for their friendship. I also thank my best friend, Na Young, for her support and statistical help and my church family at Forest Community Church for all the support and prayers. I would like to especially thank the CI children and their families who have participated in my research and the ASHA Foundation for providing me the Student Research Grant in Audiology. Lastly, my deepest gratitude is given to my family: my husband, Sean, for his unwavering support, encouragement, and love; my children, Serena and Aaron, for giving me motivation and inspiration to continue moving forward; and my parents for their unconditional love and support.

April 2018

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Children with cochlear implants (CIs) present with slower speech than their typical hearing (TH) peers. The slowed speaking rate of children with CIs has received recent attention due to the relation of speaking rate with working memory and with speech intelligibility. However, the underlying causes for the slowed speech of CI recipients are not fully understood. In this thesis, three theoretical explanations are introduced to understand how degraded auditory input affects the timing of speech. First, children with CIs may have slowed speech due to an immature internal model caused by degraded auditory feedback and the lack of auditory input. Second, the speech of children with CIs may become slower because either all or a part of speech processing stages are slowed. Third, the slowed speech of children with CIs may be influenced by paralinguistic factors, such as the intention to speak more clearly. To explore the reasons for the slowed speech of CI recipients, three experiments were performed. A first experiment explored the effects of chronological factors (such as age of implant and duration of CI experience) and performance factors (such as language ability and speech perception) on the speaking rates of 75 children with CIs and 54 children with TH at four to eight years after implantation. Results showed that speaking rate was significantly slower in the CI group than the TH group, confirming previous reports. Maturation and the amount of the auditory input were important to speaking rate, supporting the immature internal model hypothesis. Out of performance factors, language ability was the best predictor of the speaking rate of children with CIs, suggesting that the speed and accuracy of linguistic processing may be a key to the slowed speech of children with CIs. A second experiment explored whether the slowed speaking rate of children with CIs results from impairments at particular linguistic levels (lexical, syntactic, phonetic/articulatory) of speech processing and whether the speaking rates at these levels are related to working memory. Results indicated that the speaking rates of participants with CIs showed the greatest reduction compared to their TH counterparts when engaged in syntactic level processing. Also, the speaking rates for the syntactic task showed the strongest relationship with children's memory span, suggesting syntactic processing could be an important factor in the relation between speaking rate and memory. A third experiment investigated whether paralinguistic factors are involved in the slowed speech of children with CIs. Twelve teenagers with CIs and twelve counterparts with TH were asked to repeat short sentences "as fast as possible," at their habitual speed, and "slowly and clearly." Results showed that participants with CIs were able to increase their rate but their rate changes for the slow/clear condition was not statistically significant, suggesting that the slowed speech of participants with CIs may be due to strategic choice, rather than cognitive or physical limitations. Overall, the results of these three experiments suggest that the slowed speech of CI recipients are influenced by multiple factors, including maturation, CI experience, and linguistic and paralinguistic components. Implications for clinical practice are discussed.

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CHAPTER 1

INTRODUCTION

People develop the ability to speak at an age-appropriate speed and to control their rate of speech based on appropriate social situations. Defective auditory input is a known factor for inappropriate speaking rate, as found in several studies reporting a slow speaking rate in hearing impaired populations with hearing aids (Girgin, 2008; Hood & Dixon, 1969; Leder et al., 1987) and with cochlear implants (CIs) (AuBuchon, Pisoni, & Kronenberger, 2015; Chuang, Yang, Chi, Weismer, & Wang, 2012; Kronenberger, Colson, Henning, & Pisoni, 2014; Perrin, Berger-Vachon, Topouzkhanian, Truy, & Morgon, 1999; Tobey et al., 2003; Uchanski & Geers, 2003).

Despite years of work describing the speaking rate of children with CIs, the underlying relationship between degraded auditory input and the slowed speaking rate of these CI recipients remains unclear. One possible cause for the slowed habitual speaking rate in children with CIs is problems with the internal model (Perkell et al., 2000). According to Perkell (2000), the speech internal model is a representation that uses sensory and auditory feedback to map desired sounds into speech by shaping the vocal tract. The model requires auditory feedback to be developed and maintained. With maturation, the model increases its accuracy in producing sequences of speech sounds. During speech production with a mature internal model, speech movement bypasses the need for continuous direct auditory feedback. According to this view, mature and fluent speech relies on feedforward processes in controlling acoustic, goal directed movement. For children with typical hearing (TH), these learning and mapping processes occur during speech acquisition with the help of intact auditory feedback. Over time, the speech production of children with TH becomes more fluent, requires less effort, and becomes faster. However, children with CIs may have difficulties in assembling an adequate internal model due to defective auditory feedback. Consequently, children with CIs may a show slowed habitual speaking rate because of inefficient use of feedforward processing. Current data from high school-aged CI recipients show a smaller speaking rate gap between the CI children and the age-matched TH children compared with these same groups examined at the elementary school age (Geers, Pisoni, & Brenner, 2013). However, the CI group still showed a significantly slower speaking rate than the TH group and did not completely catch up in speaking rate development. Exploring the effects of various factors, such as duration of CI use or age, affecting speaking rate of children with CIs would provide a better understanding of how their auditory deficits influence the internal model.

Cochlear implants contribute to improved communication through enhanced auditory feedback for individuals with severe-to-profound sensorineural hearing loss. Numerous studies have described improved speech and language outcomes in CI recipients (Van Lierde, Vinck, Baudonck, De, & Dhooge, 2005). However, one of the challenging issues to explore in the speech production of CI recipients is the large individual differences in their speech and language outcomes. Many different variables are reported to be related to the outcomes of CI recipients. One type of variable is “chronological factors,” including age of implantation (AoI), duration of deafness, duration of CI experience (hearing age), and chronological age (CA). Exploring the relation between these chronological factors and speaking rate is potentially important because the effects of AoI and duration of deafness may suggest a benefit to early auditory access, addressing brain plasticity of speaking rate development and helping to determine an optimal surgical implantation age (Habib, Waltzman, Tajudeen, & Svirsky, 2010;

Tomblin, Barker, & Hubbs, 2007). In addition, data addressing CA and the duration of CI experience (hearing age) may be used to test the claim that maturation and auditory feedback are important to build and maintain the internal model of speech production (Perkell et al., 1997; Perkell et al., 2000).

Another variable potentially affecting CI recipients’ speaking rate may be auditory speech perception. Speech perception scores have been found to be closely related to speech and language production performance in the CI population (Chen, Wong, Zhu, & Xi, 2017; Phillips et al., 2009). Exploring the relation between speech perception and the speaking rate of the CI group is expected to suggest the effects of auditory ability to build and maintain the internal model.

An important clinical issue for individuals with CIs is the relationship between speaking rate and speech intelligibility (SI). SI may be considered in a broad sense to describe any of several measures between talker, signal, and listener (Fontan et al., 2015; Kent, Weismer, Kent, & Rosenbek, 1989). Here, SI refers not to how people with CIs are listening, but how their speech is understood by others, i.e., how much of the CI speaker’s speech is understandable by healthy listeners, essentially a production measure of CI speech (Kent, Miolo, & Bloedel, 1994). Previous studies have reported a positive relationship between intelligibility and speaking rate in the hearing impaired population, including individuals with hearing aids (Hood & Dixon, 1969) and with CIs (Girgin, 2008; Metz, Schiavetti, Samar, & Sitler, 1990; Tobey et al., 2003). One remaining question is the direction of this relationship, whether speaking rate influences SI, or SI impacts speaking rate. Speaking rate and SI data collected longitudinally may answer this question and may be beneficial both theoretically and clinically.

Language ability after implantation is closely related to speaking rate. Previous studies have reported that the faster speaking rate of CI participants are significantly related to better language scores and to better working memory (WM) after implantation (Geers & Sedey, 2011; Pisoni & Geers, 2000). Although several studies suggest a close relation between speech perception, SI, language abilities, and speaking rate of CI recipients, few studies have explored longitudinal changes in these relationships. Exploring the longitudinal relations between these performance variables and speaking rate is expected to suggest how individuals' auditory, speech, and cognitive/linguistic abilities develop and are related to speaking rate. In previous papers, authors have suggested speed and efficiency of phonological processing (Geers & Sedey, 2011; Pisoni, Kronenberger, Roman, & Geers, 2011) and/or lexical representation and encoding (Pisoni et al., 2011) as possible underlying explanatory factors for the strong correlation of WM, speaking rate, and language. However, the relationships between these processing levels and speaking rate have not been explored longitudinally.

Another potential explanation of slow speaking rate is associated with delays in speech processing time. In the well-known psycholinguistic models of Garrett (1975) and Levelt (1989), several stages are proposed to account for speech processing, including message generation, lexical retrieval, grammatical and phonological encoding, and articulation. Several studies have suggested these stages contribute to the processing of TH individuals' speaking rate. For instance, speed and accuracy of the articulation stage, determined by motor skill and coordination ability, is hypothesized to affect the speaking rate of speakers with TH (Kent & Forner, 1980; Smith & Goffman, 1998). In contrast, Laganaro et al. (2012) claim lexical retrieval speed is the key factor in the speaking rate of TH speech. Other studies have concluded that more than one level of processing is involved in the speaking rate of the TH group, such as both lexical retrieval and articulatory movement (Green, Moore, Higashikawa, & Steeve, 2000; Moore, & Maassen, 2004).

One way to explore the relationship between speech production processes and speaking rate is to present different degrees of cognitive/linguistic demands and determine whether increasing task demands results in slower speaking rate. In these studies, it is assumed that speech production processing time is altered by manipulating the type of speaking task and the complexities of stimuli. For example, for TH speakers, speaking rate generally gets slower for speech tasks which are more cognitive/linguistically demanding, from repeating syllables, to reading words, to describing pictures (Bona, 2014; Duchin & Mysak, 1987; Kaushal, Sharma, Munjal, & Panda, 2011). In addition, phonologically, lexically, and syntactically complex speech tasks may successively and incrementally require more processing time (Kleinow & Smith, 2000; Meyer & Gordon, 1985; Morrison, Hirsh, Chappell, & Ellis, 2002; Oldfield & Wingfield, 1965; Reilly et al., 2013; Ruder & Jensen, 1972). These increased linguistic demands are reported to result in increased speech errors (Page, Madge, Cumming, & Norris, 2007) and slowed reaction times (Spencer & Rogers, 2005), which may, in turn, lead to slower speaking rate. Increasing processing demands is expected to result in slower speech production rate (Bose, van Lieshout, & Square, 2007; Silverman & Ratner, 1997).

Memory is an important factor potentially related to the speaking rate of pediatric CI recipients. Variously termed “working memory” (WM), or more appropriately “short-term memory” (STM) when assessed by a forward digit span, this cognitive capacity has recently been investigated in several studies of children with CIs (Cleary, Pisoni, & Geers, 2001; Harris et al., 2013). For children with CIs, low memory capacity has been documented to be associated with slowed verbal rehearsal speed, as measured by speaking rate (Burkholder & Pisoni, 2003; Dillon, Burkholder, Cleary, & Pisoni, 2004; Pisoni & Geers, 2000). However, the key factor underlying the relationship between memory and speaking rate remain poorly understood. Exploring the relationship between variously measured speaking rates (such as at different linguistic levels; words vs. sentences) and memory would provide more information about the underlying linguistic factors involved in the relationship between STM and speaking rate in children with CIs.

In addition to the cognitive/linguistic factors that may influence children's speaking rate, it may be asked whether the lack of auditory input affects the ability to volitionally control speaking rate. Several studies suggest that typically hearing speakers change their speaking rates based on a volitional adjustment or as a response to certain speaking situations (Longhurst & Siegel, 1973; Manson, Bryant, Gervais, & Kline, 2013; Summers, Pisoni, Bernacki, Pedlow, & Stokes, 1988). This type of rate adjustment falls under the category of "paralinguistic processing." An important part of paralinguistics is to specify interactional information, or changes based on conversation and social situations. For example, speakers may choose to slow their speaking rate in order to speak more clearly (Longhurst & Siegel, 1973; Picheny, Durlach, & Braida, 1986), to match the conversation partners' speaking rate (Manson et al., 2013), or to give a certain impression (such as being more professional or more persuasive) (Smith, Brown, Strong, & Rencher, 1975). Although speaking rate adjustment is important in effective communication, studies have not explored how lack of auditory input affects the ability to control speaking rate. As a preliminary study, this thesis will examine whether school-aged CI recipients can adjust their speaking rate on request to the same extent as age-matched speakers with TH can. The results will address whether the slowed speaking rate of CI recipients is influenced by the use of paralinguistic factors. For instance, it might be the case that children with CIs reduce their speaking rates to deliver their message clearly to the listeners. Alternatively, they may simply imitate the speaking rate of testers. There is evidence for such behavior in the clear speech literature with typically hearing speakers (Kondaurova, Bergeson, & Xu, 2013; Longhurst & Siegel, 1973; Picheny et al., 1986).

The first aim of this study is to explore the influence of chronological factors (AoI, duration of deafness, duration of CI experience (hearing age), and chronological age (CA)) and performance variables (speech perception, SI, and language) on the development of speaking rate in pediatric CI recipients. This is intended to explore whether there is a benefit of early access to auditory feedback, as would be indicated by a strong effect of duration of deafness and AoI on speaking rate (Blamey et al., 1996; Geers et al., 2003; Geers et al., 2002), and to determine the extent to which physical maturation and hearing experience play a role in building and maintaining the internal model for age-appropriate speaking rate. In addition, these data address how well linguistic ability, speech perception, and speech production abilities can explain change in the speaking rate of children with CIs over time.

The second aim of this study is to determine whether the speaking rate slowdown of pediatric CI recipients corresponds with a systematic problem at all levels of linguistic processing (e.g., phonetic/articulatory, lexical, and syntactic) or whether a particular linguistic domain plays a more prominent role in this speech rate problem. This study also examines how STM is related to speaking rate at different linguistic levels in order to better understand previously described relationships between STM and speaking rate in the CI population.

The third aim of this study is to determine if children with CIs show differences from TH children in controlling speaking rate change (e.g., when asked to volitionally alter their speaking rate by speaking “as fast as possible,” “using a comfortable rate,” or “clearly and slowly”). This will address the extent to which CI recipients’ slowed speech is a result of compensatory strategies to speak more clearly.

CHAPTER 2

LITERATURE REVIEW

Speaking rate characteristics of the hearing-impaired population

In previous studies, the speaking rate of individuals with profound hearing loss who wear hearing aids has been reported to be slower than their TH counterparts (Girgin, 2008; Hood & Dixon, 1969). One of the first studies about the speaking rate of subjects with hearing impairment was conducted by Hood and Dixon (1969). Researchers measured sentence and syllable duration of 22 males with prelingual deafness and 10 TH males and reported that deaf subjects produced a significantly longer total sentence and syllable duration than TH males. More recently, Girgin (2008) compared speaking rates of 25 high school students who were profoundly hearing impaired and Turkish-speaking with speaking rates of a group of 15 students with TH. The speaking rates of students with hearing loss were statistically slower than those of their counterparts.

To understand slow speaking rate characteristics of subjects with hearing impairment, several studies have explored how either sounds or pauses are prolonged. Speaking rate comprises the duration of sound and the duration of pauses. Subjects with hearing aids showed longer duration of both sound and pauses (Choi, 2001; Hood & Dixon, 1969). Hood and Dixon (1969) found that both syllable and pause durations of adults with deafness are longer than those of TH adults. Choi (2001) measured the speaking rate of 20 school-aged children with hearing impairment wearing hearing aids and found slower articulation rates and longer total pause duration than their age-matched TH counterparts. She analyzed pauses in detail, and children with hearing aids showed a larger pause proportion, more frequent pauses, and more pauses within words than children with TH. In general, pauses between words or phrases are appropriate, and pauses within words are usually inappropriate.

Early research suggested that inappropriately prolonged sounds and more frequent pauses produced by individuals with profound hearing loss are caused by deviant breathing control (Feudo, Zubick, & Strome, 1982; Forner & Hixon, 1977; Itoh & Horii, 1985). Forner and Hixon (1977) noted respiratory movement problems in 10 male speakers with deafness, related to language programming, mechanical respiratory modification, and laryngeal and upper respiratory tract adjustment. Feudo and colleagues (1982) stated that eight adults with profound hearing loss showed a larger range of air flow and expiratory duration compared to TH adults, indicating mismanagement of airflow. Itoh and Horii (1985) analyzed airflow and volume of 12 adults with profound hearing loss and reported participants with hearing impairment used more air per syllable with more frequent inspirations and shorter expiration than their TH counterparts. Participants with hearing impairment also inhaled at linguistically inappropriate spots. The failure of airstream management was related to the lack of auditory feedback in the individuals with hearing loss, since auditory information helps to program articulatory movement (Perkell et al., 2000).

Along with airstream management problems, slow and inaccurate articulator motor control has been reported in subjects with hearing aids (Elfenbein, Hardin-Jones, & Davis, 1994; Smith, 1975). For example, Farsi-speaking adults with profound hearing loss and wearing hearing aids showed slower diadochokinesis (DDK) rates and slower speaking rate than TH controls, supporting the articulatory/physiological control theory (Seifpanahi, Dadkhah, Dehqan, Bakhtiar, & Salmalian, 2008). Overall, previous studies about speaking rate characteristics in speakers with hearing aids have suggested that these subjects speak slower than their TH counterparts, with both longer sound and pause durations, with the failure of airstream management suggested as a reason for slow speaking rate.

Speaking rate characteristics in CI recipients

With the invention of CIs, people with severe-to-profound hearing loss can receive better auditory stimulation than was possible from hearing aids (Van Lierde et al., 2005). Despite this improved hearing, the rate of their speech is still reported to be slower than that of TH controls across many studies (Chuang et al., 2012; Leder et al., 1987; Perrin et al., 1999). For instance, Leder and colleagues (1987) reported that speaking rates of 25 adults with CIs were significantly slower and durations were longer than the control group of 10 TH males, regardless of sentence length. Similarly, Perrin et al. (1999) analyzed four French-speaking CI children's voice parameters and compared them with a TH control group. They found sentence duration is longer in children with CIs compared to TH children. Chuang and colleagues (2012) studied 24 Mandarin-speaking children with CIs and 24 matched TH control children and reported children with CIs produced significantly longer sentence duration than children with TH.

The literature reporting either sound prolongation or pause prolongation (or both) for individuals with CIs has been mixed. Chung and colleagues (2012) showed longer inter-word pause duration and bigger pause proportions for children with CIs than their TH counterparts, but their data showed no statistically significant difference for articulation rate (Chuang et al., 2012). However, other studies reported longer sound productions by subjects with CIs, such as specific vowels (Neumeyer, Harrington, & Draxler, 2010), affricates (Liker, Mildner, & Sindija, 2007), and primary stressed syllables (Patil, Sindhura, & Reddy, 2010), compared to productions by TH individuals. For example, Neumeyer and colleagues (2010) compared vowel production of two groups of German-speaking CI users (young and old group) with age-matched TH groups and found speakers with CIs produced significantly longer /e:/ and /i:/ vowels than their TH counterparts. Similarly, Liker and colleagues (2007) analyzed the vowel, fricative, and affricate sound production of 18 Croatian-speaking children with CIs. They found that durations for the affricates are longer when produced by children with CIs than their TH counterparts, and that the durations decreased with therapy. Patil and colleagues (2010) examined acoustic features of the primary stressed syllable of seven Telugu-speaking children with CIs and their counterparts using a two to three minute narrated speech sample. The researchers noted a significant difference between mean duration of stressed syllables spoken by children with CIs and TH children. Taken together, these studies suggest speakers with CIs produce longer sounds than their TH counterparts. However, these studies analyzed specifically targeted sounds or syllables and did not calculate whole sentence speaking duration and pauses, so they are difficult to compare with the results of Chuang et al. (2012) in which no significant group differences in duration were reported. In summary, most studies suggest that talkers with CIs speak slower than their counterparts do, with prolonged sound and/or pause duration.

Unfortunately, few researchers have identified factors (such as linguistic, paralinguistic factors, or speech processing issues) underlying the slow speaking rate of CI recipients. Some indirect evidence suggests that air stream management failure is a reason for the slow speaking rate of speakers with hearing aids. However, this may not be the reason for the slow speaking rate of speakers with CIs since subjects with CIs have been shown to use more appropriately prolonged sounds and pauses than hearing-aided profound hearing impaired subjects, as well as fewer articulation errors and close to normal articulator movement speed (DDK) (Eskander et al., 2014; Tobey, Pancamo, Staller, Brimacombe, & Beiter, 1991; Van Lierde et al., 2005).

Chronological factors affecting the speaking rate of the CI users

Cochlear implantation facilitates the oral communication development of children with HI, including their speech production (Blamey et al., 2001; Miyamoto, Kirk, Robbins, Todd, & Riley, 1996; Spencer, Tye-Murray, & Tomblin, 1998). However, the speech and language outcomes after implantation demonstrate large individual differences based on many factors beyond hearing status, including speaker characteristics (e.g., duration of deafness, age of implantation, chronological age), implant characteristics (e.g., speech processing strategies, dynamic range), and social and educational characteristics (e.g., socioeconomic status) (Dorman, Loizou, Fitzke, & Tu, 1998; Tobey et al., 2003). Of these factors, duration of deafness and age of implantation (AoI) may address brain plasticity of speaking rate development, while chronological age (CA) and duration of CI experience (hearing age) may address the influence of physical maturity versus hearing experience. These variables are somewhat related because duration of CI experience (hearing age) can be calculated by subtracting AoI from CA, and duration of deafness can be calculated by subtracting onset of deafness from AoI. Also, the time before the onset of deafness represents a period of normal hearing experience, as opposed to the duration of CI experience which reflects a period of degraded auditory experience. For example, if a child is five years old on a testing date (CA=60 m), age of implantation is 18 months (AoI=18 m), onset of deafness is 6 months, then this children's duration of CI experience is 3.5 years (hearing age=42 m) and duration of deafness is 12 months (Fig. 2.1). Several studies have suggested that earlier implantation, shorter duration of deafness, and longer CI experience are related to better speech and language outcomes after implantation, although some studies suggested that speech language outcomes were only related to duration of CI experience (hearing age) and not to CA (Huang, Yang, Sher, Lin, & Wu, 2005; Phillips et al., 2009). These data are potentially important because they suggest that physical experience with auditory input is more important than biological maturation. In all, the relations between these chronological factors and speaking rate development are not fully understood. Therefore, a deeper investigation of chronological factors and speaking rate development is essential.

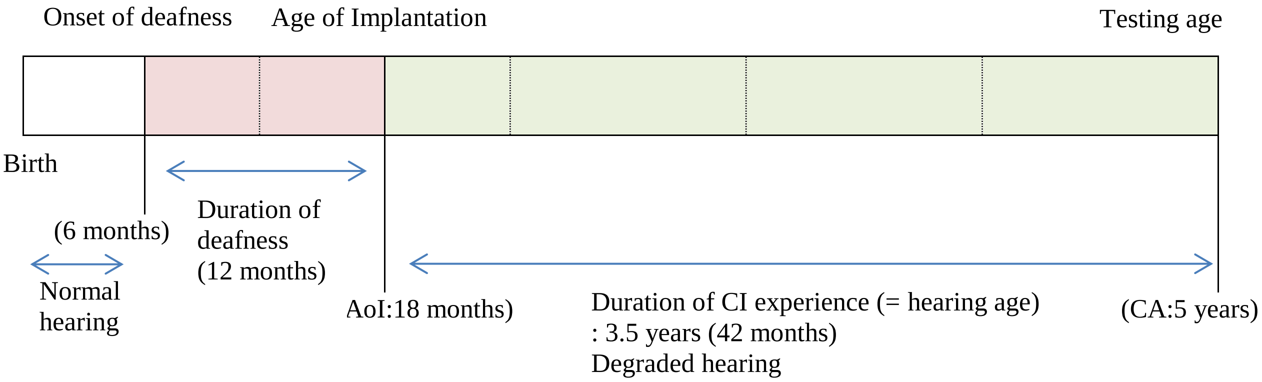

Figure 2.1. An example of a child's age of implantation (AoI), duration of deafness, duration of CI experience (hearing age), and chronological (CA) measures.

Age of implantation (AoI) and duration of deafness

Cochlear implantation stimulates the auditory nerve with electrical pulses and helps children with hearing loss to develop speech perception and receptive and expressive language abilities. Children implanted at a younger age show better results in speech perception, language, and intelligibility development than children implanted at an older age (given onset of deafness at birth), supporting the idea that earlier implantation is better (Lohle et al., 1999; Loundon, Busquet, Roger, Moatti, & Garabedian, 2000; Tomblin et al., 2007; Tye-Murray, Spencer, &

Woodworth, 1995). In the early 1990s, implantation as late as 10 years old was considered early enough to facilitate speech perception development (Dawson et al., 1992). The recommended AoI decreased to under five years old within a few years, although there was controversy regarding the temporal limits of the hypothesized sensitive period for speech perception development (Robinson, 1998). Several studies suggest implantation before five years of age is beneficial (Lohle et al., 1999; Loundon et al., 2000; Tye-Murray et al., 1995). For example, a group of children implanted before five years of age produced significantly higher speech perception scores than the other groups of children implanted between five and eight or between eight and 15 years of age (Tye-Murray et al., 1995). Fryauf-Bertschy, Tyler, and Kelsay (1997) found that children implanted between two and five years of age demonstrated better speech perception than children implanted later than age five. A more recent study reported children who received CIs before the age of two had significantly better speech perception scores than children implanted at a later age (Svirsky, Teoh, & Neuburger, 2004).

Several studies also suggest a sensitive period for language development after cochlear implantation (Tomblin et al., 2007). Holt and Svirsky (2008) studied word recognition and receptive and expressive language development in four groups of children who received CIs at different ages: 6-12 months, 13-24 months, 25-36 months, and 37-48 months. The first group demonstrated better receptive language development than the other groups but did not show the advantage of early implantation in receptive language development. The groups of children implanted before the age of two demonstrated better overall performance and spoken word recognition improved in all groups (implanted up to four years old). Similarly, a large cohort study of children with CIs provided evidence that children implanted before 18 months showed significantly accelerated language development up to three years after cochlear implantation, compared to other groups (implanted 18-36 months, after 36 months) (Niparko et al., 2010). Tobey and colleagues (2013) investigated spoken language scores of 160 children from the cohort study at four, five, and six years after cochlear implantation and found younger implantation, especially before 2.5 years, is associated with improved spoken language abilities. A recent multicenter study in Australia reported that children who were implanted before one year showed significantly higher speech production and language scores than children implanted later than one year, suggesting the critical period for language development may occur as early as one year of life (Dettman et al., 2016). A positive relationship between early implantation and improved SI development is also demonstrated in several studies (Habib et al., 2010; Huang et al., 2005; Svirsky, Chin, & Jester, 2007). In conclusion, AoI predicts speech perception and speech and language productions. In other words, earlier implantation leads to higher speech and language outcomes.

A related question concerns what to expect if a CI recipient has a short duration of deafness. Studies of postlingual CI recipients investigating the onset of deafness and duration of deafness have shown that these are important factors predicting speech perception outcomes (Blamey et al., 1996; Friedland, Venick, & Niparko, 2003; Leung et al., 2005). In addition, later onset of deafness was related to better language outcomes for children with CIs, suggesting the importance of early access of auditory signal (Geers et al., 2003; Geers et al., 2002). Although duration of deafness has been less studied than AoI for prelingual CI recipients, it is important to compare outcomes between CI recipients who are born deaf and CI recipients who were able to hear then progressively lost hearing, as this may help better understand brain plasticity for audition.

Duration of CI experience (hearing age) and CA

Longer duration of CI use leads to better speech and language production, as has been shown in many studies (Chen et al., 2017; O'donoghue, Nikolopoulos, & Archbold, 1999; Phillips et al., 2009). However, the effects of CA on speech and language outcomes are mixed. For example, one study reported intelligibility scores were correlated with CA and duration of implant use in 51 children with CIs (Chin, Tsai, & Gao, 2003), but another study only found a correlation between intelligibility and duration of CI use and failed to demonstrate a relationship between CA and intelligibility scores (Huang et al., 2005). Also, SI scores are more highly correlated with hearing age (duration of CI use) than with CA in participants implanted before age three (Flipsen & Colvard, 2006). Duration of CI use represents the importance of hearing and is often called hearing age, while CA represents the importance of physical maturation. Since speaking rate increases over time and it has been suggested that mental and physical maturation is important to speaking rate development, exploring the effect of hearing age and CA on the speaking rate of pediatric CI recipients is essential.

For speaking rate changes over time, two articles have reported the effect of CI experience on speaking rate of adults with CIs (Evans & Deliyski, 2007; Kishon-Rabin, Taitelbaum, Tobin, & Hildesheimer, 1999). Kishon-Rabin and colleagues (1999) studied acoustic and perceptual speech production of five Hebrew-speaking adults with post-lingual deafness before implantation and at one, six, and 24 months post-implantation. They found word and sentence duration decreased over time. Evan and Deliyski (2007) analyzed acoustic characteristics, including the speaking rate of three deaf adults at pre-implant and two weeks, one month, three months, and six months post-implant. Speech rate was measured for reading and spontaneous speech. The results showed speech rates of deaf adults were slower than their counterparts with TH, and one participant showed a trend of faster speaking rate for both reading and spontaneous speech over time, while the other two showed no changes in their speaking rates. Thus, both studies found the speaking rate of CI recipients faster with longer CI experience; however, these studies used a small number of participants. Since the participant groups are so small (five for Kishon-Rabin and colleagues (1999), and three participants for Evan and Deliyski (2007)), this potentially limits generalization. Another potential limitation of these two studies is that the age period examined was not long enough to reveal long-term effects of cochlear implantation. Kishon-Rabin et al. (1999) reported the speaking rate of CI users up to 24 months and Evan and Deliyski (2007) reported up to six months.

A preferred study design to explore the effect of duration of CI experience and CA is longitudinal because investigating speech production improvement using cross-sectional designs often fails to show successful changes over time. For example, in a study by Montag et al. (2014), there was no effect of CI duration on intelligibility improvement, and the result even shows a negative relationship between duration of CI use and speech intelligibility. However, as the authors note, this appears largely due to different factors across participants, especially older speech processing strategies and later age at implantation of participants who used CIs longer. To better analyze the effect of duration of CI experience and CA and speaking rate changes over time, it is preferable to use a longitudinal study design, including long-term tracking and large groups of CI recipients.

Performance variables and speaking rate

In addition to chronological factors, exploring the effects of performance variables on speaking rate development are of theoretical and clinical importance. In this section, the relation between speech perception, SI, and language abilities and the speaking rate of CI recipients are reviewed.

Speech perception and speaking rate

Speech perception ability is an important factor affecting speech and language outcomes of the CI population. Speech perception development is highly correlated to vocabulary development (Chen et al., 2017). In addition, several studies indicate a significant positive relationship between speech perception and production for subjects with HIs (Archbold et al., 2000; O'donoghue et al., 1999; Phillips et al., 2009). SI is strongly correlated with speech perception between two to five years after implantation (O'donoghue et al., 1999). One study investigated the relationship between speech perception and intelligibility of 117 children with CIs for the first five years after implantation in three countries (United Kingdom, Iran, and Turkey) and reported strong correlations between the speech perception measurements and SI scores (Phillips et al., 2009).

Pisoni and Cleary (2003) noted a strong correlation between speaking rate and digit span (short term memory; STM) of children with CIs. The researchers also examined speech perception scores and proposed the following "three-way" relationship between these three performance variables: speech perception scores were strongly related to speaking rate, and speaking rate was strongly related to short term memory (STM), even when other demographic variables such as age at duration of deafness, duration of implant use, number of active electrodes, and chronological age at test were partialled out. However, the relation between speech perception and STM was not statistically significant. Exploring the relation between these performance variables in a longitudinal study is expected to clarify how (and perhaps why) these variables change over time. Given that one of the three components investigated in this three-way relationship is production based (i.e., speaking rate), several studies have examined the link between speaking rate and SI. Many studies have reported that SI scores are strongly correlated with speaking rate in the HI population, and this issue will be therefore reviewed in the next section.

Speech intelligibility and speaking rate

Speech intelligibility (SI) is one of the most important factors needed when people want to communicate using oral language (Gold, 1980; Kent et al., 1994; Whitehill & Ciocca, 2000). As noted previously, here SI will refer to how accurately TH listeners understand the speech of individuals with HI (including those with CIs), taken as an index of the speech production abilities of HI people. Children with pre-lingual deafness using CIs obtain higher SI scores than children using hearing aids or tactile aids (Geers & Tobey, 1995; Osberger, Maso, & Sam, 1993). SI after implantation is higher when the duration of CI use is longer (Calmels et al., 2004; Chin, Finnegan, & Chung, 2001; Chin et al., 2003; Huang et al., 2005) and when the AoI is younger (Habib et al., 2010; Svirsky et al., 2007). For example, Tobey and colleagues (2011) reported SI improved about 20% from 8-9 years old (with an average 5 years and 3 months of CI use) to 15-18 years old (with an average 13 years and 3 months of CI use), suggesting SI scores increase steadily up to high school age with longer CI use. Also, Svirsky, Chin, and Jester (2007) showed implantation before the age of two years resulted in significantly higher SI scores than did later implantation.

Several studies support the idea that faster speaking rate is related to better SI of individuals both with hearing aids and CIs. Parkhurst and Levitt (1965) investigated 40 children with hearing loss and demonstrated a negative relationship between sentence duration and intelligibility, which improved with training in sound duration. Hood and Dixon (1969) collected a speech rhythm rating of adults with profound hearing loss, which is a general perception of suprasegmental features excluding articulation errors. The researchers found that speech rhythm rating and SI scores are highly associated with the speaking rates of deaf males. Metz and colleagues (1990) studied the relationship between segmental and suprasegmental characteristics, including sentence duration and intelligibility of 40 college students with hearing loss, and found longer sentence duration was associated with poor segmental production and lower SI scores. This relationship was also found in languages other than English. Girgin (2008) found a significant negative correlation between speaking rate and intelligibility of 25 Turkish-speaking high school students with hearing aids.

For pediatric CI recipients, Tobey and colleagues (2003) observed a negative relationship between sentence duration and intelligibility in children with CIs. When exploring 181 eight to nine-year-old CI recipients' acoustic characteristics, including sentence duration, only 23% of participants produced sentence durations within the same range as their TH counterparts (Uchanski & Geers, 2003). They also found a significant difference in the sentence durations of children with CIs depending on communication mode. Only 9% of children using total communication were within the range of their age-matched TH counterparts, while 36% of children in the oral communication mode were within the range of the TH children’s sentence duration. Taken together, data indicate a strong effect of speaking rate on the intelligibility of the speech produced by individuals with CIs.

Language and speaking rate

Successful language development after cochlear implantation is of major interest to researchers for both theoretical and practical reasons. As mentioned before, language development is known to be related to early implantation and better speech perception scores (Holt & Svirsky, 2008; Niparko, Tobey, Thal, Eisenberg, Wang, & Quittner, 2010; Tomblin et al., 2007). In addition, recent studies have explored the effect of cognitive factors on the language abilities of CI recipients in order to reveal variables underlying language development after implantation. Specifically, research has focused on the relationship between working memory, verbal rehearsal speed (which is measured by speaking rate), and the language abilities of CI recipients (Geers & Sedey, 2011; Pisoni & Geers, 2000).

Geers et al. (2011) reported long-term language outcomes of 112 participants with CIs by using standardized tests. The participants were tested twice, at eight to nine years old and 16-17 years old. The results showed that digit span and speaking rate at younger ages (elementary school age) strongly predict language scores at high school age. Also, when participants recalled more numbers and spoke faster at high school age, their language scores were significantly higher than at younger ages. In their discussion, the authors suggested “speed and efficiency of phonological processing” as an underlying explanation. Based on previous studies which have shown pediatric CI recipients’ phonetic/articulatory, lexical, and syntactic difficulties (de Hoog et al., 2016; Geers & Hayes, 2011; Le Normand, Ouellet, & Cohen, 2003; Nittrouer, Sansom, Low, Rice, & Caldwell-Tarr, 2014; Spencer et al., 2003; Tavakoli, Jalilevand, Kamali, Modarresi, & Zarandy, 2015; Warner-Czyz, Davis, & Macneilage, 2010), the slow speaking rate of CI recipients may logically be caused by processing difficulties at any of the linguistic levels described in Levelt's model (1992) (i.e., message generation, lexical retrieval, grammatical encoding, phonological encoding, and articulation). In summary, the question of which level(s) are responsible for CI users' slow speaking rate needs to be tested empirically.

Speech production and speaking rate

Following classical models of speech production (Garrett, 1975; Levelt, 1992) one may suppose that a delay in processing at specified levels (i.e., message generation, lexical retrieval, grammatical encoding, phonological encoding, and articulation) may cause slowed speech output (Levelt, 1992). As briefly discussed in the Introduction, proposed factors for the slowed rate of people with hearing impairment include cognitive/linguistic ability and articulation speed. Traditionally, articulator speed and accuracy are suggested as key factors for individual differences in speaking rate of TH speakers, based on the assumption that maturation of articulation motor control is related to faster speaking rate over time (Kent & Forner, 1980; Smith & Goffman, 1998). However, more recent findings have suggested cognitive and linguistic abilities are more important to speaking rate variation than articulator movement speed for individuals with TH (Mefferd & Corder, 2014; Nip & Green, 2013). Nip and Green (2013) examined the relationship between the kinematics of articulator movement and speaking rate of six age groups: ages four, seven, 10, 13, 16 years, and adults. Lip and jaw movements were measured by a three-dimensional motion capture system. There was a significant increase in speaking rate at ages four, seven, 10, and 13, but the increase was not associated with increase in articulatory movement and speed. A recent study conducted by Mefferd and Corder (2014) investigated articulatory movement speed and the overall speaking rate of different ages of adults, from young to very old. They found that lip and jaw peak speed was not related to speaking rate, supporting the results of Nip and Green (2013), although lip and jaw stiffness affected speaking rate decline in the older adults. Taken together, these kinematic results suggest that speaking rates of TH talkers are not directly associated with articulatory movement speed.

Cognitive/linguistic demands and speaking rate

Several studies have shown that speaking rate is associated with the cognitive/linguistic demands of speaking tasks (Kleinow & Smith, 2000; Nip & Green, 2013). One way to manipulate cognitive/linguistic demands experimentally is to use different types of speech tasks (such as picture description, naming, and reading). For TH speakers, speaking rate generally gets slower when the speech task type places more demands on speech processing (Bona, 2014; Duchin & Mysak, 1987; Kaushal et al., 2011). For instance, Kaushal and colleagues (2011) examined the speaking rate of 20 Punjabi native speakers and found their speaking rate in picture description was slower than their speaking rate in reading. Since the processing demand is the smallest in reading, reading is usually the fastest task. Similarly, Duchin and Mysak (1987) examined the speaking rate of young, middle-aged, and old adults for picture description, conversation, and reading and found that speech rate is the slowest for picture description and the fastest for reading. In recent research, Bona (2014) analyzed the speaking rate and articulation rate of young and old adults and found both young and old adults spoke slowest during recall and fastest while reading aloud, regardless of measurement type (either speaking rate or articulation rate). Nip and Green (2013) reported speaking rates were slower when speech tasks were more cognitively demanding (such as storytelling or repeating sentences) than when speech was simple (in tasks such as diadochokinesis (DDK)), for both children and adults with TH. Taken together, these studies suggest that manipulating the type of speech task affects speaking rate because different types of speech tasks require different amounts of cognitive/linguistic demands.

Another way to change the cognitive/linguistic demands in speaking tasks is to manipulate the complexity of the contents. For example, more phonologically complex speech tasks require more phonological/articulatory processing time. Low phonotactic probability and high phonemic similarity of sound sequences are associated with increased processing time based on phonological encoding and articulation demands (Meyer & Gordon, 1985; Reilly et al., 2013). Similarly, processing vocabulary with low frequency and late age of acquisition requires more time for the lexical retrieval (and phonological encoding) level than processing vocabulary with high frequency and early age of acquisition (Morrison et al., 2002; Oldfield & Wingfield, 1965). Also, syntactically more complex sentences arguably require more processing time for syntactic organization. In support of this claim, Ruder and Jensen (1972) investigated the relationship between syntactic complexity and speaking rate of eight to 12-year-old children and found speaking rate is slower and sentences are produced with more pauses when they are more complex. Overall, these findings demonstrate that manipulating the complexity of linguistic content affects speaking rate.

Short-term memory (STM) and speaking rate

A cognitive factor known for important relations with speaking rate is working memory (WM), more appropriately termed “short-term memory” (STM) when assessed by digit span.

According to phonological loop theory, a “phonological loop” (or articulatory loop) consists of a phonological store which holds memory for a limited time and an articulatory process in which sub-vocal rehearsal of verbal information is revived before it is forgotten (Baddeley & Hitch, 1994; Baddeley, Thomson, & Buchanan, 1975). Therefore, if one’s speaking rate is faster, there would be more information placed in the phonological loop before forgetting occurred (Cowan et al., 1994; Hulme, Thomson, Muir, & Lawrence, 1984; Hulme & Tordoff, 1989). For example, Hulme and colleagues (1984) examined the relationship between word duration and the memory span of 36 typically developing subjects categorized into four age groups: 3-4 years, 7-8 years, 10-11 years, and adults and found statistically significant main effects and interaction of speaking rate and age on STM. Hulme and Tordoff (1989) also explored the relation between speech rate and memory span of four to ten years old children with typical development and found a linear relationship between speaking rate and WM.

Recent interest in WM of people with CIs has greatly increased. Researchers are trying to understand the large individual differences in speech and language outcome of people with CIs by exploring neurocognitive functions (AuBuchon et al., 2015; Kronenberger et al., 2014). Studies have compared the WM of CI recipients with their TH counterparts and found lower verbal WM scores of individuals with CIs (AuBuchon et al., 2015; Harris et al., 2013; Soleymani, Amidfar, Dadgar, & Jalaie, 2014). Soleymani and colleagues (2014) examined the non-word repetition and forward and backward digit span of 50 Farsi-speaking five to seven-year-old children with CIs and 50 age-matched TH children. The children with CIs showed significantly lower WM in all tasks. Results also showed that WM was negatively correlated with AoI and positively correlated with duration of CI experience or hearing age. In addition, WM of children with CIs was better when AoI was younger and duration of CI experience was longer. Harris and colleagues (2013) in a longitudinal study reported delayed WM development of 66 children with CIs and found that baseline working memory predicted later speech and language outcomes.

Several studies have reported a statistically significant relationship between speaking rate and verbal WM of participants with CIs (Burkholder & Pisoni, 2003; Dillon, Pisoni, Cleary, & Carter, 2004; Pisoni & Cleary, 2003). Pisoni and colleagues (1999) studied the relation between the speech, language, and speech perception abilities of 160 children with CIs and their memory span. The authors reported a strong correlation between overall sentence duration and digit span. In a later study, Pisoni and Cleary (2003) measured forward and backward digit span for the verbal memory capacity and spoken sentence duration of 36 McGarr sentences spoken by 176 children with CIs. Results revealed a strong correlation between speaking rate and digit span, even after statistically removing variables affecting the outcome. Burkholder and Pisoni (2003) focused on the communication mode of the 37 participants and found that the children with CIs who use total communication had shorter digit spans and slower speaking rates than those using oral communication. Similarly, Dillon and colleagues (2004) used accuracy of non-word repetition to measure verbal working memory and found that speaking rate contributed strongly to accuracy of non-word repetition. In summary, there is broad support for the notion that speaking rate is related to WM in both TH talkers and individuals with hearing impairment, including those with CIs.

Paralinguistic factors affecting speaking rate

Several paralinguistic factors have been reported to account for the speaking rate changes of speakers with TH. First, people tend to slow down to make their speech clearer (Picheny et al., 1986). This slow-down strategy is often observed, especially when listeners are notably old or young, non-native speakers, have speech/language problems, or have hearing problems. For example, work by Picheny et al. (1986) showed that talkers with TH speak slowly when asked to speak clearly as if speaking to HI listeners. Speakers also slow down their speaking rate when they think they are not well-understood by others. Longhurst and Siegel (1973) examined the speech of 30 college-aged students under conditions when the speech was not successfully conveyed to the listener and found that people speak slower, with longer descriptions, and with more redundant speech under these conditions. Also, talkers produced more pauses and longer segments with additional phonological changes, including less vowel modification and more released stop bursts than their habitual speech.

Talkers may choose their speaking rate as a representation of the self-image they wish to express through their speech. For example, fast speaking individuals are positively perceived as “competent” and/or “ambitious,” while slowly speaking individuals are viewed as “professional” and/or “polite” (Brown, Giles, & Thakerar, 1985; Fujihara, 1986; Ray, 1986; Smith et al., 1975). Previous studies have shown that depression symptoms include slowed speech and slowed cognitive processing, suggesting that talkers temperament may be an important factor in speaking rate (Kivelä & Pahkala, 1988; Nilsonne, 1987). Another paralinguistic factor affecting speaking rate can be interactive alignment, when a person imitates the speech of the other speaker, including the rate of speech (Garrod & Pickering, 2004). In both dialogue and repetition situations, participants imitate the suprasegmental features of the other person's speech, including rate of speech, accent, and loudness (Manson et al., 2013).

Tsao and Weismer (1997) investigated the relative importance of paralinguistic factors in the speaking rate of individuals with TH by contrasting a paralinguistic hypothesis and a neuromuscular hypothesis. The paralinguistic (or sociolinguistic) hypothesis suggests an individual speaks either fast or slow to express themselves in their desired image. The neuromuscular hypothesis suggests individual talkers have different neuromuscular limitations, and these limitations will determine an individual's speaking rate. To test these hypotheses, the researchers chose 50 fast speakers and 50 slow speakers based on their daily speaking rate and asked them to speak as fast as they could. The results showed both groups were able to increase their speaking rate at the same ratio. According to the researchers, this result supports the neuromuscular hypothesis that biological factors are the main determinant in speaking rate.

A related question is how the lack of auditory input affects the ability to control speaking rate by request or by situation. We may hypothesize that speakers with CIs are not able to increase or decrease speaking rate because of their degraded auditory feedback. Alternatively, speakers with CIs may be able to modify their speaking rates and this can be understood by paralinguistic factors. According to this hypothesis, speakers with CIs slow down their speaking rate strategically to speak clearly and to deliver a message better to listeners because of the need to compensate for their relatively low SI (Tobey, Geers, Sundarrajan, & Shin, 2011). In addition, the slow speaking rate of speakers with hearing impairment may result from their imitation of conversational partners, since people speak slower with partners with hearing impairment than with individuals with TH (Kondaurova et al., 2013; Longhurst & Siegel, 1973). Finally, most studies that report the slow speaking rate of CI users specified no desired rate of speech (e.g., habitual or fast) and instead had participants repeat individual testers' speech models. Therefore, there is a possibility that previous speaking rate data reflect participants simply copying slowly modeled speech (i.e., not tapping the participants' own speaking rates). These issues have not been explored in CI recipients.

Summary and Research Questions

In this section, research about speaking rate characteristics of individuals with hearing aids and CIs were reviewed. An ongoing challenge is to understand the underlying reasons for the documented slowed speaking rate of CI recipients. Of many different factors, four chronological factors and three performance measures were reviewed. The four chronological factors are age of implantation (AoI), duration of deafness, duration of CI experience (hearing age), and chronological age (CA). AoI appears to be an important factor affecting speech and language outcomes in children deaf from birth, and may be related to a sensitive period of auditory input in speech perception, speech production, and language development (Habib et al., 2010; Tomblin et al., 2007). Duration of deafness is a good predictor of speech perception and language production for children with acquired hearing loss, presumably associated with the benefit of very early "normal" auditory input. Two other major factors affecting speech and language outcomes of CI users are CA and the duration of CI use (hearing age), as both maturation and auditory input are required to build and maintain an internal model for speech production. Exploring the relationships between chronological factors and speaking rate is expected to give a better understanding concerning a sensitive period of speaking rate development, early auditory access benefits, and the effect of hearing experience and physical maturation. These variables are highly related to individuals with CIs' speech and language outcomes but are not fully understood in terms of their effects on speaking rate development.

Other factors thought to explain individual differences of speaking rate development are performance measurements, including speech perception, SI, and language abilities. All of these factors are known to be related to speaking rate; however, whether these relations change over time and which are the best predictors of speaking rate have not been explored. Examining these performance variables and the speaking rate of CI users can address the role of auditory feedback, spoken language ability, and cognitive linguistic abilities on speaking rate development.

Two factors have been adduced to explain the speaking rate variation of TH talkers, a lower level motor constraint and a cognitive/linguistic processing constraint. Recent findings suggest motor movement speed is not related to speaking rate, but cognitive/linguistic demand is. These results suggest cognitive/linguistic ability in TH talkers is more important for speaking rate variation than lower level articulatory factors (Mefferd & Corder, 2014; Nip & Green, 2013). However, the manner in which these speaking task demands affect the speaking rate of CI recipients has not been fully explored. Knowing how participants' speaking rates change as a function of different linguistic demands will help determine which speech production processing stages most strongly affect CI recipients' speech output. Also, discovering how memory capacity is related to speaking rates at different linguistic demands may suggest the underlying reasons for the observed relation between memory and speaking rate.

Paralinguistic factors affecting the speaking rate control of speakers with TH were also reviewed. Paralinguistic factors associated with slowed speaking rate include the motivation to speak clearer (Longhurst & Siegel, 1973; Picheny et al., 1986), to match the conversation partners' speaking rate (Manson et al., 2013), and to give a certain personal impression (such as being more professional or more persuasive) (Smith et al., 1975). For the speaking rate of talkers with TH, a previous study has suggested paralinguistic factors may not play a dominant role in intrapersonal speaking rate differences (Tsao & Weismer, 1997). However, the slowed speech of speakers with CIs may well be influenced by paralinguistic factors, perhaps because they wish to speak slower and more clearly or to imitate a conversational partner's slowed speech. Alternatively, the slowed speaking rate of CI recipients could be due to their own limitations from degraded auditory feedback. An impaired ability to control and/or change speaking rate would support this hypothesis. Since little is known about paralinguistic factors affecting the speaking rate of CI recipients, further research is needed. This research can potentially lead to better opportunities for speaking rate rehabilitation and more effective CI use.

Research questions and hypotheses

The purpose of this dissertation is to address the possible influences of chronological factors, and performance variables, linguistic processing difficulties, and paralinguistic factors on the slow speaking rate of CI recipients. Research questions and predictions are the following:

Research questions for Experiment 1. Is the speaking rate of children with CIs at four to eight years after implantation slower than the speaking rate of age-matched children with TH? Are the chronological factors (age of implantation (AoI), duration of deafness, duration of CI experience (hearing age), and chronological age (CA)) related to longitudinally-collected speaking rate data? What are the relationships between pediatric CI recipients' longitudinally-collected performance variables; namely, speech perception, speech intelligibility (SI), language scores, and speaking rate?

Hypotheses: Based on previous studies, several hypotheses will be tested to determine whether children with CIs lack a stable internal model for fluent speech production because of degraded auditory feedback. We hypothesize:

1) The speaking rate of participants with CIs will be slower than the speaking rate of their age-matched TH counterparts.

2) Speaking rate will remain slower for CI recipients over time (i.e., speaking rate measures obtained annually over five years) compared to TH age-mates.

3) Earlier implantation (both earlier AoI and shorter duration of deafness), a longer duration of hearing experience (hearing age), and physical and cognitive maturation (CA) will be associated with more normal (i.e., faster) speaking rate in CI users. Of the chronological factors tested, duration of hearing experience will predict speaking rate the best. This hypothesis is based on previous findings (Huang et al., 2005; Flipsen & Colvard, 2006) and assumes an internal model that must be maintained and adjusted with auditory information (Perkell et al., 1997; Perkell et al., 2000).

4) Of the performance variables (speech perception, SI, and language abilities), speech perception will best predict the speaking rate of children with CIs because auditory feedback is required to develop and maintain the internal model for speaking rate.

Research questions for Experiment 2. Does speaking rate slowdown in individuals with CIs correspond to a systematic problem at all levels of linguistic processing (e.g., phonetic/articulatory, lexical, and syntactic), or does a particular linguistic domain play a more prominent role in this slowed speech? If there is any particular linguistic domain responsible for slowed speech, is it also the underlying factor responsible for the previously-reported strong relation between WM and speaking rate?

Hypotheses: 1) CI participants will show significant speaking rate slowdown only in response to particular components of the grammar. This can be called a "selective degradation hypothesis" (e.g., as supported by Tomblin et al., 2015). Based on the close relation between language ability and speaking rate, the speaking rate difference between the CI group and the TH group is expected to be larger for sentence tasks than non-sentence tasks, suggesting selective impairment of levels of the grammar.

2) The correlation between STM (measured by digit span) and speaking rate will be stronger when speaking rate is measured for the sentence or the word stimuli, as opposed to non-word tasks. This is based on the previous studies reporting a strong relationship between language, speaking rate, and STM (Geers & Sedey, 2011; Pisoni & Geers, 2000).

Research questions for Experiment 3. Are children with CIs able to adjust speaking rate when asked to speak faster or slower? Will children with CIs show a smaller percentage change in adjusted speech rate, compared to TH children?

Hypothesis: Compared to their age-matched counterparts, children with CIs will exhibit smaller (or nonexistent) changes in speaking speed upon being requested to volitionally change their speaking rate. This would suggest that control of speaking rate is affected by reduced auditory feedback in children with CIs. Alternatively, if children with CIs are able to increase and decrease speaking rate as well as (or better than) their counterparts, this may suggest that the slowed speaking rate of CI recipients is a compensatory strategy to produce clearer speech.

CHAPTER 3

EXPERIMENT 1. ROLE OF MATURATION AND EXPERIENCE

This chapter presents an experiment comparing speaking rate in a CI group and a TH group. speaking rate was measured annually over a five-year period (corresponding to four to eight years after implantation in the CI group). The purpose is to determine whether speaking rate in the CI group is slower than speaking rate in the TH group and whether any difference between age-matched groups is reduced with longer use of a CI. We hypothesized that the speaking rate of participants with CIs will be slower than that of their age-matched TH counterparts, even after four years of CI experience. Furthermore, based on the internal model for speech production (Perkell et al., 2000), we hypothesize that this difference will not diminish over the next five years of device use. The internal model proposes that an individual learns how to map the movement of the vocal track during the speech acquisition period. Intact auditory feedback is required to build and maintain the internal model (Perkell et al., 1997; Perkell et al., 2000). Since the auditory input received by children with CIs is impoverished relative to TH children, we hypothesized that the slower speaking rate of children with CIs will persist regardless of how long they use their device. That is, the children in this study are presumed to have built their internal model on degraded auditory input and one also maintain this model on inadequate input, resulting in a net lag in speaking rate.

This chapter presents data addressing whether chronological factors (CA, hearing age, AoI, and duration of deafness) and performance variables (speech perception, SI, and language scores) predict speaking rate. As the internal model is improved through auditory feedback and maturation, the duration of CI use (hearing age) and CA are expected to strongly predict speaking rate. Speech perception ability is expected to be a better predictor of speaking rate than language or SI because auditory ability is important for building and maintaining the internal model. The results will suggest the effects of auditory experience, maturation, and early access to auditory input on speaking rate of children with CIs. In addition, how speech perception abilities, speech production accuracy, and linguistic ability affect speaking rate of children with CIs will be addressed.

Participants

The participants were 75 children with CI and 54 TH children. Their data was extracted from the CDaCI dataset (Fink et al., 2007). CI recipients had been recruited and tested in the following six clinical cochlear implant centers: House Ear Institute, Los Angeles, CA; Johns Hopkins University Listening Center, Baltimore, MD; the University of North Carolina, Chapel Hill, NC; the University of Miami, Miami, FL; the University of Michigan, Ann Arbor, MI; and The University of Texas at Dallas, Callier Advanced Hearing Center, Dallas, TX (Fink et al., 2007). The participant selection, recruitment, and assessments were approved by the Institutional Review Board (IRB) at all six institutions. Eligible participants for the CI group were participants who were younger than five years old when recruited, pre- or post- lingually deafened, with either bilateral or unilateral CI(s), from monolingual English-speaking families. The participants were followed every six months for the first three years and then annually from the fourth year. The number of observations for speaking rate were 45 (four years after implantation), 57 (five years after implantation), 58 (six years after implantation), 57 (seven years after implantation), and 61(eight years after implantation). During the follow-ups, participants were tested on measures of spoken language, speech perception, cognition, and social skills. In this dissertation, we analyzed the independent contributions of AoI, duration of deafness, duration of CI use (hearing age), and CA on speaking rate development based on annually collected data from four to eight years after implantation. Children who had participated in at least three out of five sessions were included in the analyses. Out of 75 participants, 28 of them were male and 47 were female. Their average age at the four-year follow-up was 79.85 months (*SD* = 14.86), average AoI was 30.26 months (*SD*=14.97), and average duration of deafness was 28.26 months (*SD* = 15.02). For the TH group, out of 54 participants, 27 of them were male and 27 were female, and their average age at the four-year follow-up was 84.12 months (*SD* = 16.14). Characteristics of participants with CIs and TH are presented in Table 3.1.

Table 3.1. *Characteristics of participants in Experiment 1*

Characteristic	**Children with CIs (n= 75)**	**Children with TH (n=54)**
Age at testing (at 4 years f/u), mean (SD), mo	79.85 (14.86)	84.12 (16.14)
Duration of CI use (at 4 years f/u), mean (SD), mo	49.50 (2.97)	NA
Duration of deafness, mean (SD), mo	28.26 (15.02)	NA
Age of implantation, mean (SD), mo	30.26 (14.97)	NA
White, No. (%)	54 (72)	44 (81)
Female, No. (%)	47 (62)	27 (50)
Maternal education, HS graduate, No. (%)	71 (94)	53 (98)
Household income > $50000, No. (%)	45 (60)	49 (90)

Note. f/u = follow-up; NA= not applicable; HS= high school
Race/ethnicity classifications were based on parental reporting using categories decided by National Institutes of Health policy

Procedure

Speaking rate: Sentence durations were collected as part of the data obtained annually from four to eight years after implantation. During the data collection session, participants repeated sentences presented face-to-face in the child's preferred communication mode accompanied by a written version. When the target sentences were presented by speech, a test administrator used live voice at a comfortable rate. Stimuli included 36 McGarr sentences, which contain three, five, or seven syllables (McGarr, 1983). Each sentence has a target monosyllabic key-word selected from the corpus of words that predicts SI of deaf children (Smith, 1975). In half of the sentences (18 sentences), the key words are easily predictable (e.g., high-context sentences like "The flag is red, white, and <u>blue</u>"), and the other half contain less predictable key words (e.g., low-context sentences like "We will go to the <u>beach</u> today") (McGarr, 1983) (Appendix A). All speech stimuli were recorded and stored as audio files.

Sentence durations were measured using Adobe® Audition® software (Adobe System Corporation, San Jose, CA) after removing the silence before and after the target sentence. After checking the beginning and the end of sentences, sentence durations were noted. Next, the total number of syllables of the sentence was divided by the sentence duration in seconds. The average speaking rate (syllable/second; syll/sec) of 36 sentences was calculated for every participant with CI and TH.

Speech intelligibility (SI): McGarr sentences spoken by participants during the data collection sessions were used to collect SI data. Audio-recorded sentences were presented at a comfortable listening level to listeners who wrote down the words they heard. A total of 324 adults with self-reported normal hearing and minimal exposure to people with hearing impairment served as listeners. Most listeners were students at the University of Texas at Dallas who needed research credits for their psychology classes. We explained the procedures with written consent forms approved by the University of Texas at Dallas Institutional Review Board. To avoid familiarity effects, each listener heard only one sentence from each child. No listener heard the same sentence or speaker more than once. Sentences were presented in random order. Each sentence was judged by three listeners, and as a result, the SI of each child was judged by a total of 108 different listeners (three x 36 sentences). An intelligibility score was derived by dividing the number of correctly understood words in a sentence by the total number of possible correct words in the sentence, then converting this number to a percentage (all word intelligibility).

Speech perception: Participants' perceptual abilities were evaluated annually during the data collection sessions using several batteries, including the Meaningful Auditory Integration Scale (MAIS) (Robbins, Renshaw, & Berry, 1988), Early Speech Perception Test (ESP) (Moog & Geers, 1990), Pediatric Speech Intelligibility test (PSI) (Jerger & Jerger, 1984), Lexical Neighborhood Test and its multi-talker version (LNT, MLNT) (Kirk, Pisoni, & Osberger, 1995; Kirk et al., 1997), Phonetically Balanced Word Lists - Kindergarten (PBK) (Haskins, 1949), and the Hearing in Noise Test for Children (HINT-C) (Nilsson, Soli, & Sullivan, 1994). The speech perception batteries were selected based on participants' performance level. If the child met a criterion level of an easier test, the more difficult test was used to test the next level (to reduce floor and ceiling effects). The speech perception scores were calculated to derive a single cumulative index, the Speech Recognition Index in Quiet (SRI-Q). SRI-Q scores range from 0-600 with the low-range scores (0-100) from parent report (MAIS), mid-range scores (101-300) from closed-set testing (ESP and PSI), and high-range scores (301-600) from open-set testing (LNT, PBK, and HINT-C (tested under quiet condition)).

Language: Participants' receptive and expressive language abilities were assessed by a standardized, global language battery which measures semantic, syntactic, and discourse skills; Comprehensive Assessment of Spoken Language (CASL) (Carrow-Woolfolk, 1999). Combined scores of three subtests (word definitions, understanding spoken paragraphs, and sentence assembly) form the Language Content Index. Participants' language content index scores were obtained annually between four and eight years after implantation.

Method of analysis

Data Analysis Linear models were used to compare speaking rate development between children with CIs and children with TH at 4, 5, 6, 7, and 8 years after implantation. To identify the mean trajectories, developmental curves of speaking rate in each group were explored using nonparametric regression with locally weighted smoothing scatterplot (LOESS). Linear mixed-effects models were used to determine the effects of chronological factors (AoI, duration of deafness, duration of CI use, CA) and performance scores (speech perception scores, SI, language scores) on speaking rate. Chronological factors and performance scores served as fixed effects to understand speaking rate in the models, and child specific intercepts and slopes were used as random effects over the testing time (four to eight years after implantation). The likelihood ratio (Chisq) between the null model and the full model was used to test significance of the relationships at the level of $p<0.05$. *Akaike's* information criterion (AIC) was used to compare variables and determine which variable explains and predicts speaking rate best. AIC uses maximum likelihood factor analysis and provides information addressing how well the model fits with given fixed effects and random effects. A factor(s) with smaller AIC fits better in the model than the factor(s) with larger AIC. R program (R core Team, 2017) and lme4 package (Bates, Maechler & Bolker, 2012) were used to perform linear models and linear mixed-effects models.

Results

Participants' descriptive statistics, including average speaking rate, speech perception, language, and SI scores and standard deviations (*SD*), are presented in Table 3.2. Speaking rate differences between the CI group and the TH group were analyzed at 4, 5, 6, 7, and 8 year follow ups. In addition, the effects of chronological factors (CA, hearing age, duration of deafness, and AoI), performance variables (speech perception, SI, and language) on speaking rate development in participants with CIs were analyzed.

Table 3.2. *Participant descriptive statistics for Experiment 1*

	Testing session	**CI group, Mean (SD)** ***n*=75**	**TH group, Mean (SD)** ***n*=54**
4 years	Speaking rate (syll/sec)	2.53 (0.85)	3.38 (0.54)
	Speech perception[a]	505.13 (132.64)	N/A
	Language	74.94 (21.56)	114.22 (18.19)
	Speech intelligibility (%)	47.24 (26.17)	81.05 (10.18)

5 years	Speaking rate (syll/sec)	2.44 (0.82)	3.49 (0.56)
	Speech perception[a]	547.69 (100.91)	N/A
	Language	76.58 (23.52)	114.23 (16.01)
	Speech intelligibility (%)	56.57 (26.27)	78.61 (9.67)
6 years	Speaking rate (syll/sec)	2.75 (0.72)	3.75 (0.46)
	Speech perception[a]	577.39 (42.79)	N/A
	Language	79.34 (24.44)	116.02 (18.68)
	Speech intelligibility (%)	60.54 (23.01)	81.40 (9.50)
7 years	Speaking rate (syll/sec)	3.06 (0.76)	4.02 (0.35)
	Speech perception[a]	577.97 (33.79)	N/A
	Language	81.92 (23.54)	117.94 (15.95)
	Speech intelligibility (%)	64.36 (24.90)	79.53 (15.05)
8 years	Speaking rate (syll/sec)	3.25 (0.76)	3.78 (0.54)
	Speech perception[a]	573.63 (55.93)	N/A
	Language	85.21 (23.21)	120.14 (15.30)
	Speech intelligibility (%)	62.81 (22.01)	77.78 (16.70)

a. Note: The speech perception data measured by SRI-Q used in this thesis are corrected to include the point of mastery in each child. This step was taken because, in reviewing the data, it became clear that the raw scores entered into the multi-center database were artificially low. We found that a test administrator skipped HINT-C in quiet when a participant mastered HINT-C in quiet during the previous testing, moving to advanced speech perception testing. It resulted in a child's SRI-Q score having a certain and impossible drop in value because HINT-C in quiet was scored as 0. We found this phenomenon in over 50% of the participants and corrected the scores by replacing them with the previous highest score. We used this corrected SRI-Q score to predict speaking rate of participants with CI.

Figure 3.1. displays average speaking rate of children with CIs and their counterparts at 4, 5, 6, 7, and 8 years after implantation with standard errors. speaking rate differences between the CI group and the TH group were analyzed by linear models. Significant differences were found at four years ($F(1,77)=28.09$, $p<0.05$), five years ($F(1,100)=55.78$, $p<0.05$), six years ($F(1,96)=56.02$, $p<0.05$), seven years ($F(1,103)=67.07$, $p<0.05$), and eight years ($F(1,83)=10.05$, $p<0.05$) after implantation. Figure 3.2. shows individual trajectories of children with TH and children with CIs. Children with CIs demonstrated slower trajectories compared with children with TH, and the slopes are different from one interval to the next in both CI and TH.

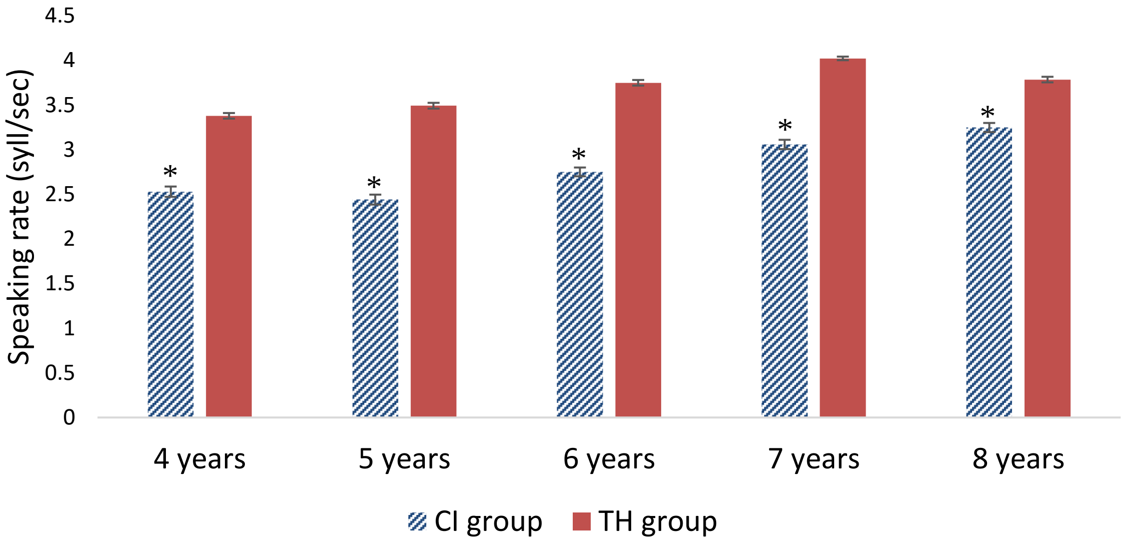

Figure 3.1. Speaking rate averages and standard errors of CI group and TH group at 4, 5, 6, 7, and 8 years after implantation

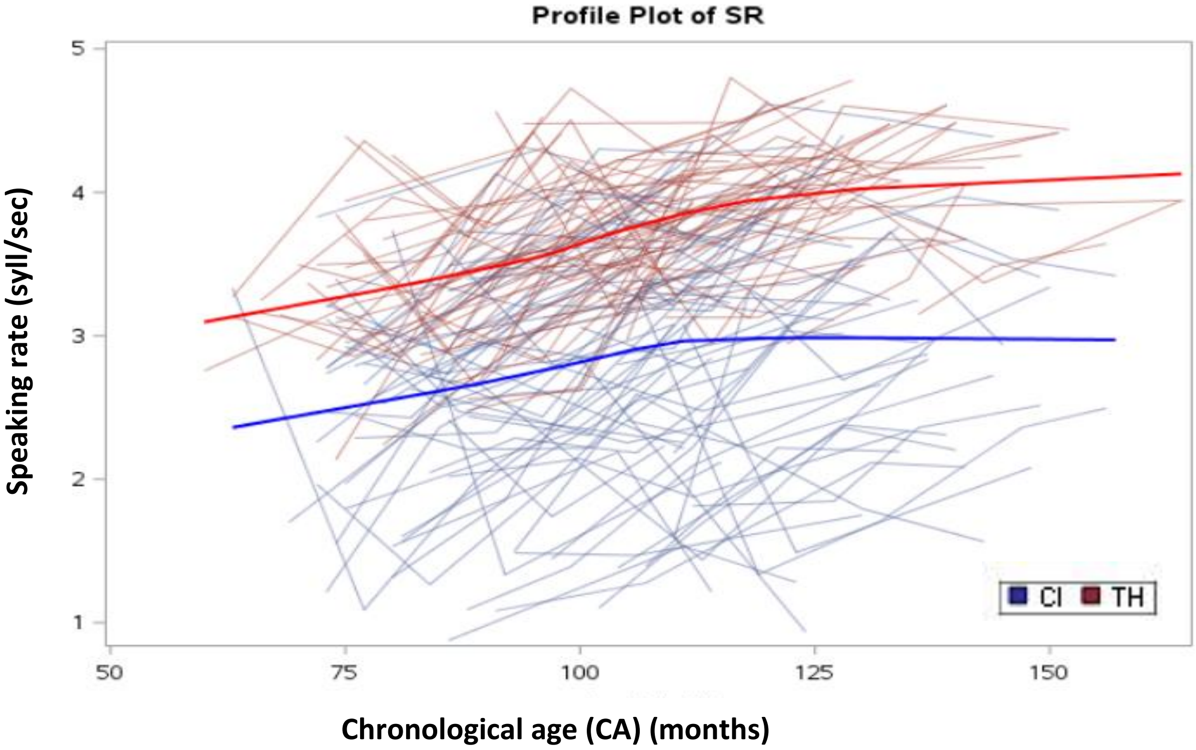

Figure 3.2. Individual speaking rate trajectories of CI group (blue) and TH group (red) with mean trajectories

Chronological variables and speaking rate

Figure 3.3. displays the speaking rate changes of individuals with CIs by their CA, with the growth curve. The effect of CA on speaking rate was analyzed by using a linear mixed-effects model. The result demonstrated that the speaking rates of children with CIs increased positively over five years as a function of CA (b = 0.015, SE = 0.0032, 95% Conf. int. = [0.008, 0.021]). This effect was statistically significant by likelihood ratio between null and model formulas (χ^2 (3) = 55.07, $p<0.05$).

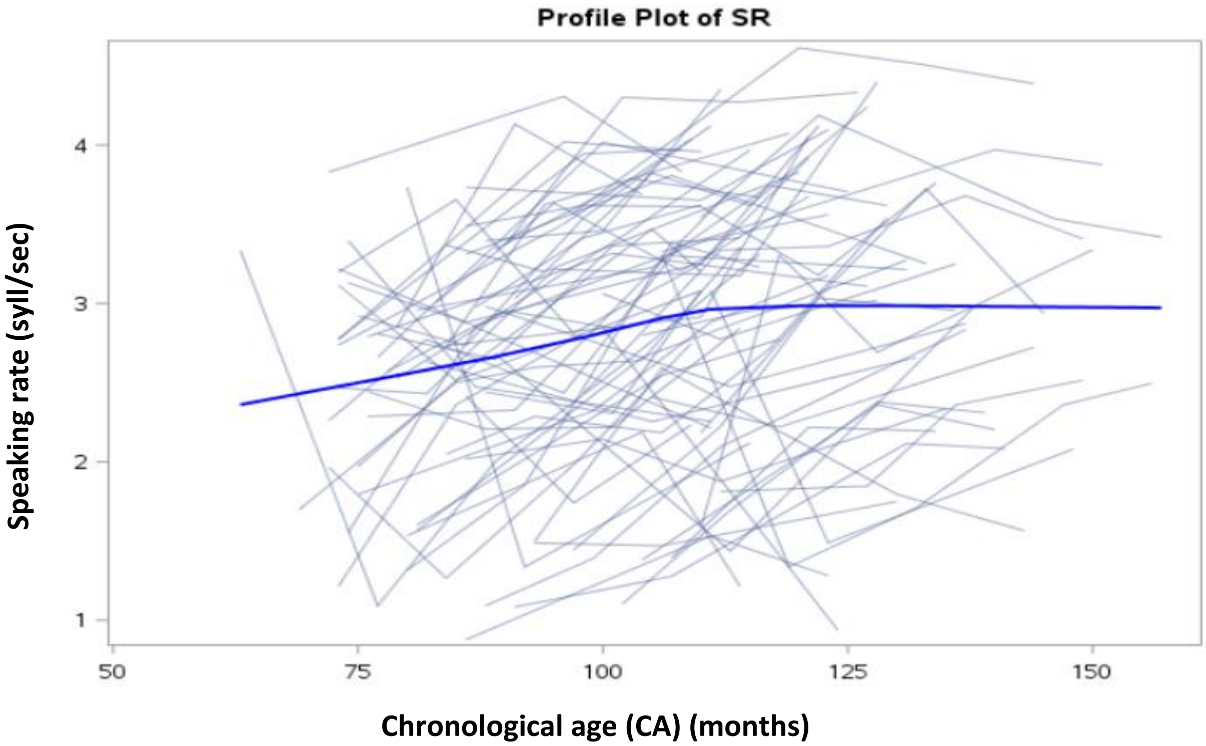

Figure 3.3. Individual speaking rate changes over chronological age (CA; months) for children with CIs (*n*= 75) with mean trajectory

The growth curve in Figure 3.4. shows how individuals' speaking rates change over time by duration of CI use with the growth curve. Using the linear mixed-effects model, it was found that speaking rate increased with duration of CI experience (hearing age) (b = 0.0174, SE = 0.0032, 95% Conf. int. = [0.01105, 0.02391]). This effect was statistically significant by likelihood ratio between null and model formulas (χ^2 (1) = 47.56, *p*<0.05).

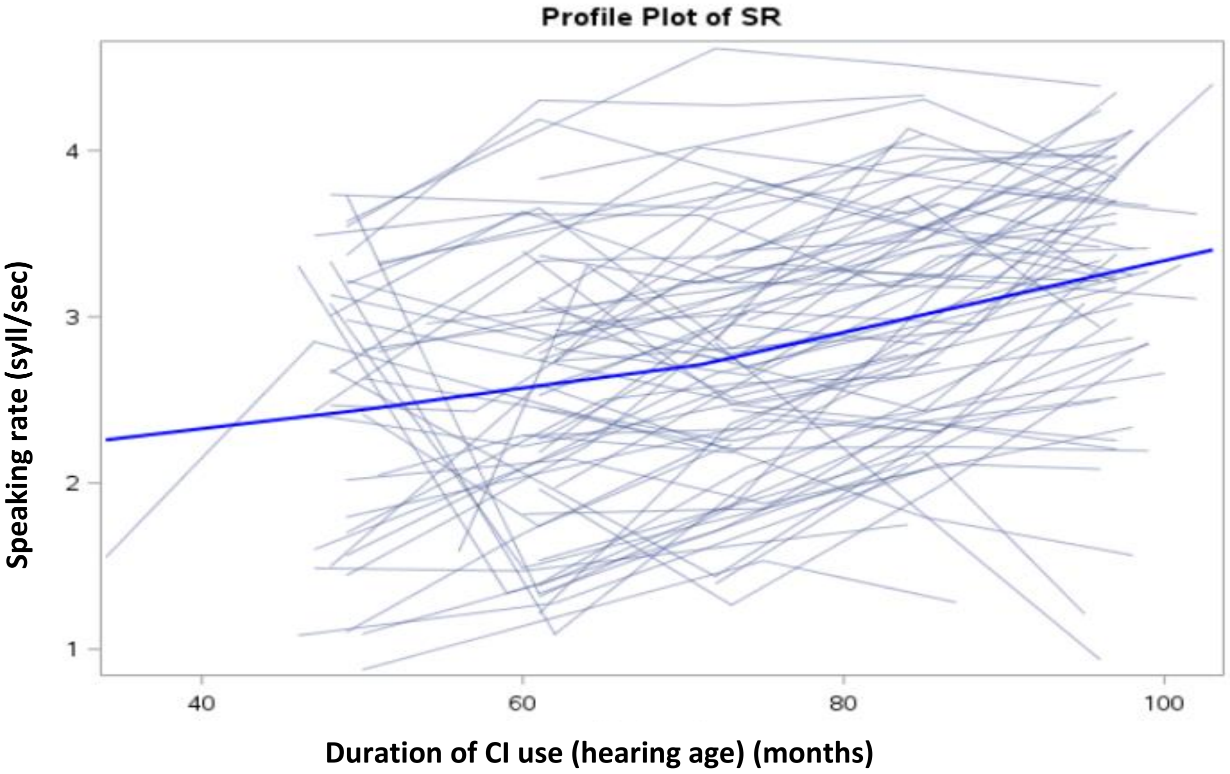

Figure 3.4. Individual speaking rate changes over duration of CI use (hearing age; month) with mean trajectory

Figure 3.5. shows the relations between duration of deafness and speaking rate at 4, 5, 6, 7, and 8 years after implantation for participants with CIs. The effect of duration of deafness on speaking rate was analyzed by using a linear mixed-effects model. The results showed that, in general, shorter duration of deafness was related with faster speaking rate (b = -0.011, SE = 0.006). However, this effect was not significant by likelihood ratio between null and model formulas (χ^2 (3) = 2.77, *p*=0.42).

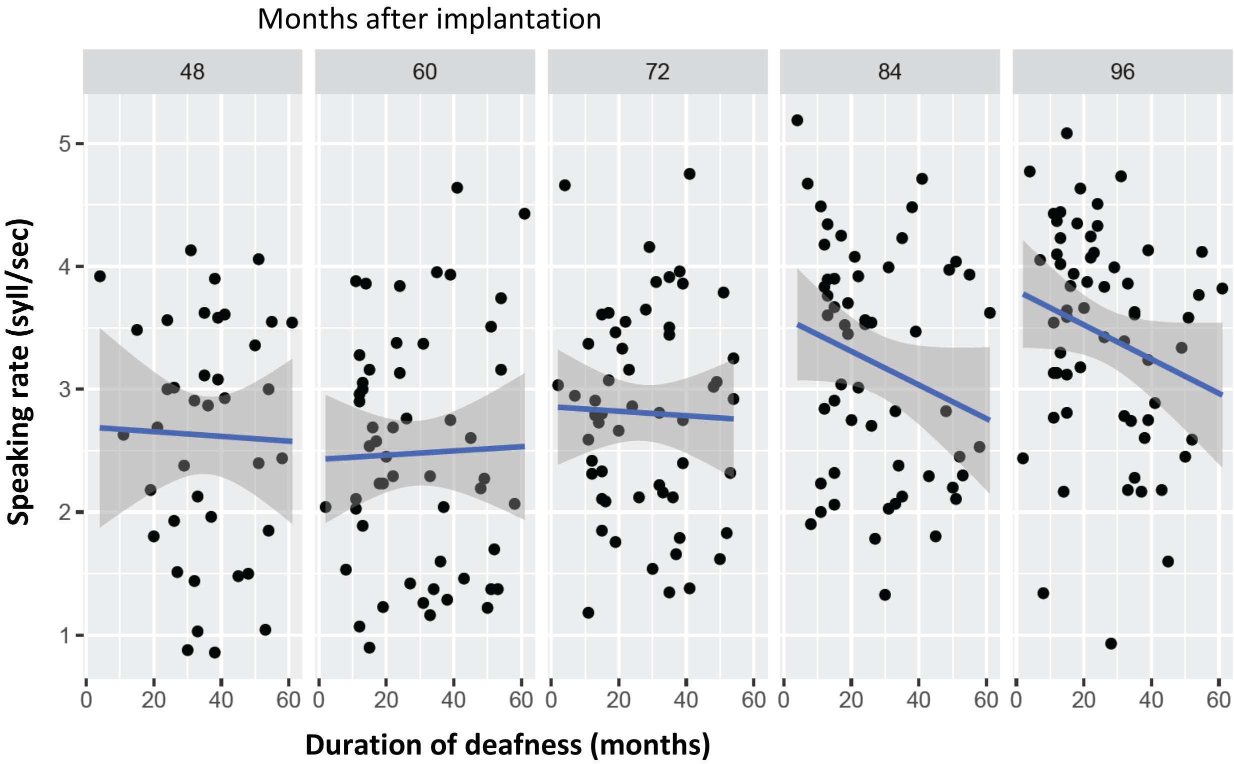

Figure 3.5. The relations between duration of deafness and speaking rate at 48, 60, 72, 84, and 96 months after implantation. Fitted regression lines and standard errors (in gray area).

The effects of AoI on speaking rate for 4, 5, 6, 7, and 8 years after implantation were analyzed in a linear mixed-effects model. As a result, earlier AoI was related with faster speaking rate (b = -0.012, SE = 0.006) (Figure 3.6.). However, this effect was not significant by likelihood ratio between null and model formulas (χ^2 (3) = 6.28, p=0.10).

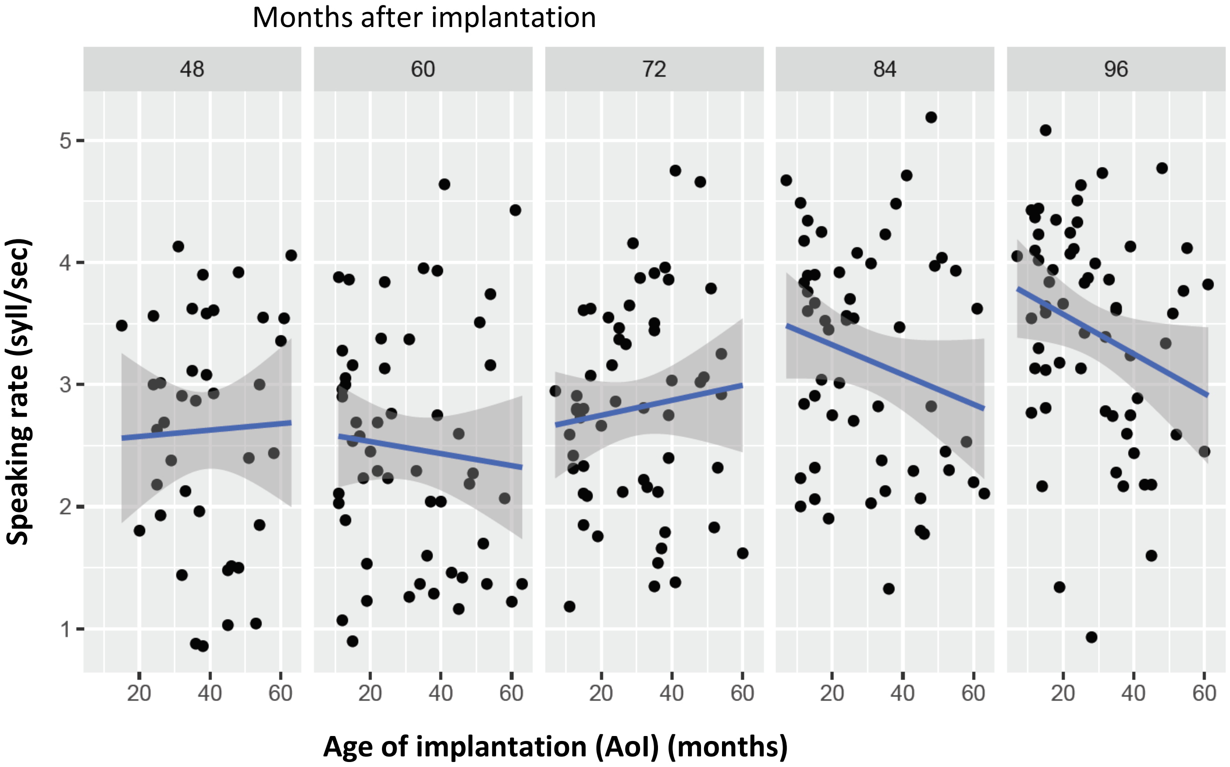

Figure 3.6. The relations between AoI and speaking rate at 48, 60, 72, 84, and 96 months after implantation with fitted lines and standard errors (gray area)

To find the best fitting model to explain speaking rate development using chronological factors, the models with different fixed effects were compared. As an independent factor, hearing age predicted speaking rate significantly better than CA, AoI, and duration of deafness (χ^2 (0) = 13.35, $p<0.05$). *Akaike's* information criterion (AIC) was the smallest for hearing age (568), then CA (581), AoI (610), and duration of deafness (611). We also added hearing age (or CA) and AoI (or duration of deafness) together in the model to find the best fitting model for speaking rate. We could not add hearing age and CA together or AoI and duration of deafness together in the same model because this would violate independence assumption. As a result, the models using both hearing age (or CA) and AoI (or duration of deafness) were able to predict speaking rate significantly. However, none of the combinations were better than hearing age, suggesting auditory experience is the most important factor for speaking rate development.

Performance variables and speaking rate

The effects of speech perception scores on speaking rate at 4, 5, 6, 7, and 8 years after implantation were analyzed in a linear mixed-effects model. We entered SRI-Q scores as a fixed effect and intercepts for subjects as random effects. The linear mixed-effects model found that speaking rate was faster when the speech perception score was higher (b = 0.002, SE = 0.0005) (Figure 3.7.). This effect was significant by likelihood ratio between null and model formulas (χ^2 (1) = 10.31, p<0.05).

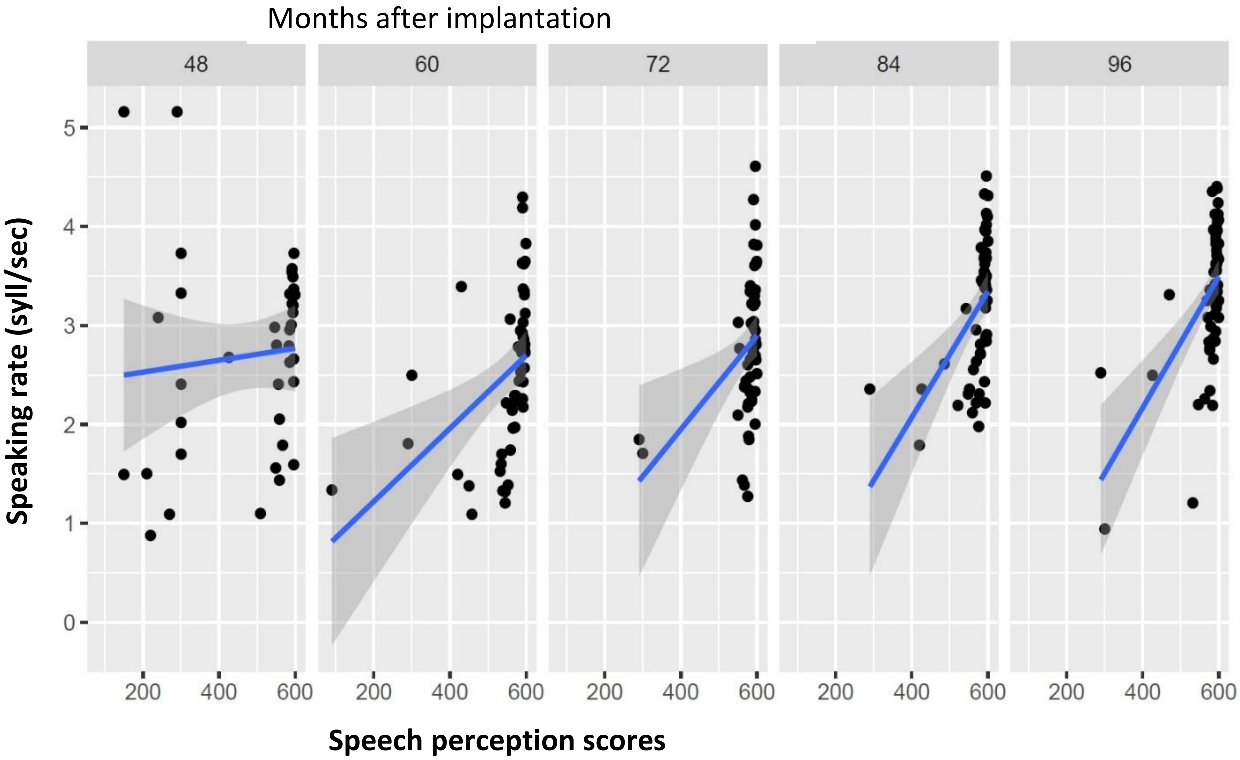

Figure 3.7. The relations between speech perception scores and speaking rate at 48, 60, 72, 84, and 96 months after implantation with fitted lines and standard errors (gray area)

To avoid the ceiling effect of speech perception scores using data collected at 4, 5, 6, 7, and 8 years after implantation, we performed an additional analysis using speech perception scores at four years after implantation as a fixed effect to predict the speaking rates at 4, 5, 6, 7, and 8 years after implantation. A linear mixed-effects model found that speaking rate was faster when speech perception score was higher (*b* = 0.002, SE = 0.0005) (Figure 3.8.). This effect was significant by likelihood ratio between null and model formulas (χ^2 (1) = 28.07, *p*<0.05). Although both SRI-Q scores at 4, 5, 6, 7, and 8 years after implantation and SRI-Q scores at four years after implantation significantly predicted speaking rate over five years, AIC was smaller for the second analysis (with SRI-Q at the four year visit) (467) than the first one (482).

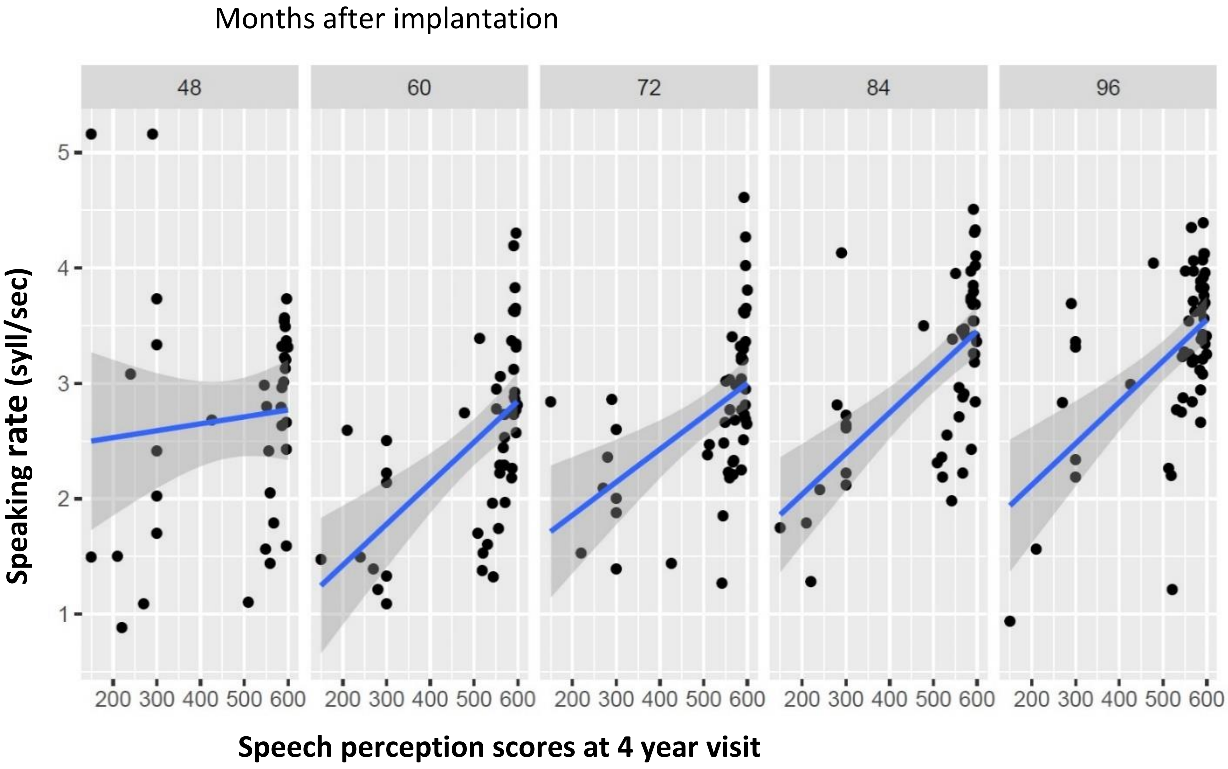

Figure 3.8. The relations between speech perception scores at the four year visit and speaking rate at 48, 60, 72, 84, and 96 months after implantation with fitted lines and standard errors (gray area)

The effects of SI on speaking rate at 4, 5, 6, 7, and 8 years after implantation were analyzed in a linear mixed-effects model. As a fixed effect, we entered SI scores and we had intercepts for subjects as random effects. In the linear mixed-effects model, higher SI scores were associated with faster speaking rate of children with CIs (*b* = 0.011, SE = 0.003) (Figure 3.9.). This effect was significant by likelihood ratio between null and model formulas (χ^2 (1) = 14.67, $p<0.05$).

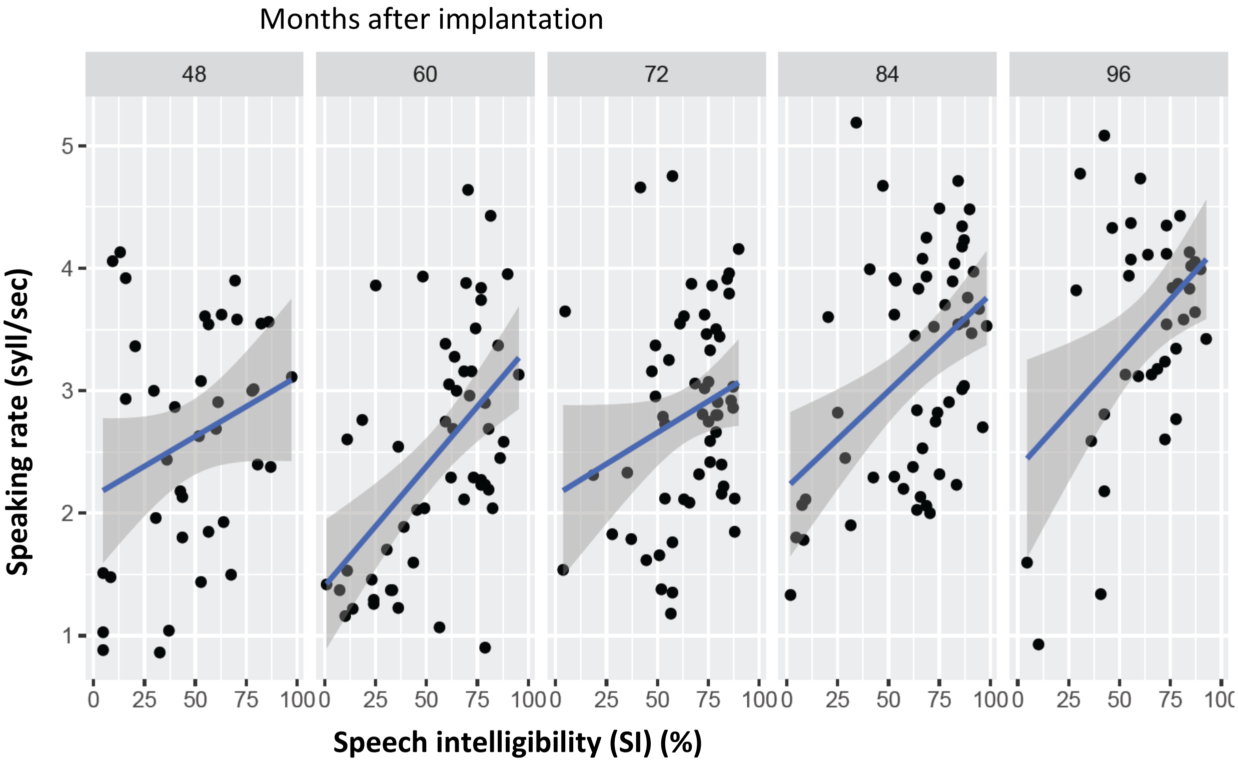

Figure 3.9. The relations between SI and speaking rate at 48, 60, 72, 84, and 96 months after implantation with fitted lines and standard errors (gray area)

The effects of language scores on speaking rate at 4, 5, 6, 7, and 8 years after implantation were analyzed using a linear mixed-effects model. We entered language scores as a fixed effect, and we had intercepts for subjects as random effects. In the linear mixed-effects model, higher language scores were associated with faster speaking rate (*b* = 0.022, SE = 0.002) (Figure 3.10.). This effect was significant by likelihood ratio between null and model formulas (χ^2 (1) = 61.52, p<0.05).

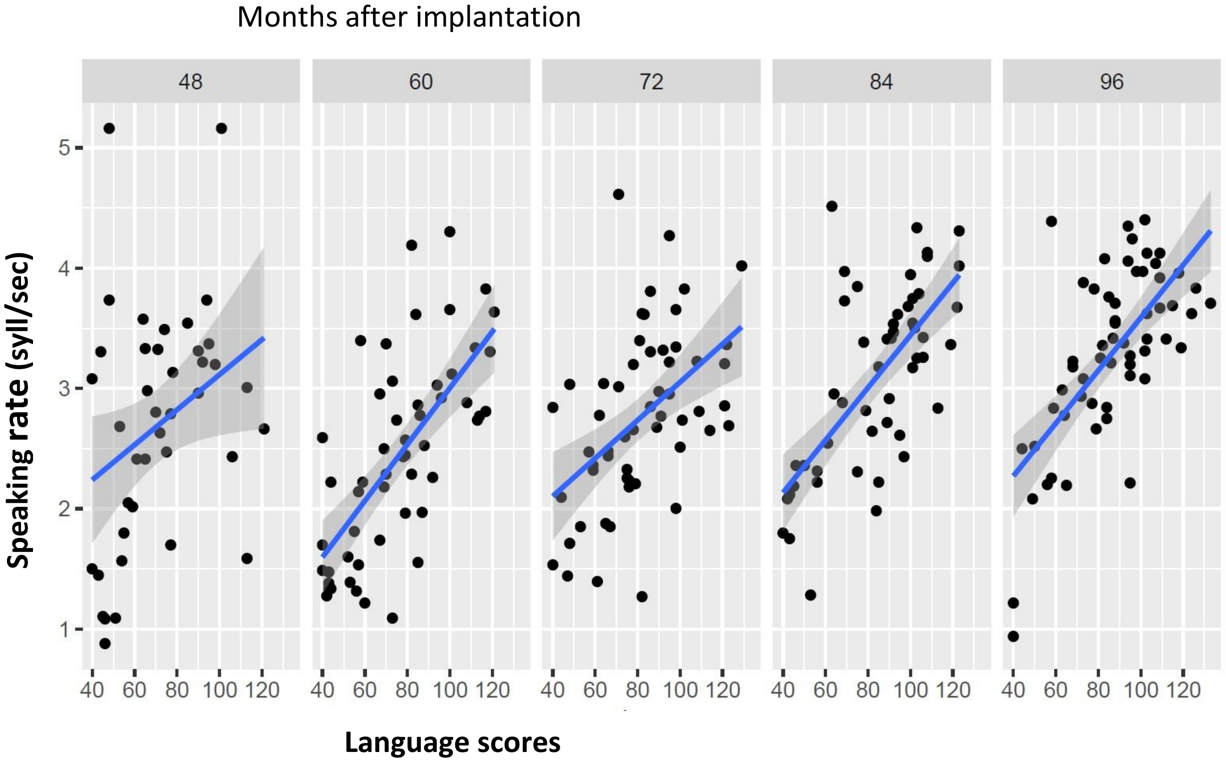

Figure 3.10. The relations between language and speaking rate at 48, 60, 72, 84, and 96 months after implantation with fitted line (blue) and standard error (gray area)

The linear mixed-effects models using performance variables were compared to find the best fitting model explaining the speaking rate of children with CIs. Unlike the prediction that speech perception scores would make the best model, the model with language ability as a fixed effect was significantly better than models with any other variables (speech perception and SI) or the combinations of variables (χ^2 (1) = 43.78, p<0.05). AIC was the smallest for the relationship between language ability and speaking rate (435), then SI (480) and speech perception (482), suggesting that out of three performance variables, language ability is the most important to predict speaking rate.

In summary, results indicate that the speaking rate of children with CIs remained slower than the speaking rate of children with TH at 4, 5, 6, 7, and 8 years post-implantation. The model with the best fit to speaking rate used hearing age as a fixed effect, suggesting the importance of hearing experience for speaking rate development. The duration of deafness and AoI failed to significantly predict speaking rate independently. Speech perception, SI, and language ability significantly predicted speaking rate, and language ability was the best predictor out of the performance variables.

CHAPTER 4

EXPERIMENT 2. ROLE OF LANGUAGE PROCESSING

Based on the psycholinguistic models of Garrett (1975) and Levelt (1989), the slowed speaking rate of CI recipients (as observed in the results of Experiment 1 and in previous literature) may have resulted from one or many speech processing levels' slowdown. Garrett (1975) and Levelt's (1989) speech production processing models include message generation, lexical retrieval, grammatical and phonological encoding, and articulation. Previous studies which explored the stages involved in the processing of a TH speaker's speaking rate have identified several different stages. Researchers suggested the processing speed at the articulation stage (Kent & Forner, 1980; Smith & Goffman, 1998), lexical retrieval stage (Laganaro et al., 2012), or both the lexical retrieval and articulation stages (Green, Moore, Higashikawa, & Steeve, 2000; Moore, & Maassen, 2004) are associated with speaking rate of TH speakers. However, the stage at which speech processing is slower in CI recipients has not been explored. It is hypothesized that lexical retrieval or syntactic processing are primarily responsible for the slowed speaking rate of CI recipients, rather than the speed of phonological processing and articulation. This hypothesis is consistent with the results of Experiment 1, in which language score was the best predictor for the speaking rate of CI recipients.

Another factor known to be related to speaking rate of children with CIs is STM, as described in the phonological loop theory. According to this theory, sub-vocal rehearsal is used to form a "phonological loop" to store memories for a limited time before forgetting (Baddeley & Hitch, 1994; Baddeley et al., 1975). This theory was supported by finding a close relationship between the STM and speaking rate of children with TH and CIs, mostly measured using sentence level stimuli (Burkholder & Pisoni, 2003; Dillon, Burkholder, Cleary, & Pisoni, 2004; Pisoni & Geers, 2000). Examining the correlation between STM and speaking rate, measured at various linguistic levels (such as syllables, words, and sentences) would further explore this relationship. For example, if the relationship between memory and speaking rate only relied on the phonological loop, a correlation between word level speaking rate and digit span would be predominant. On the other hand, if more syntactic processing were involved in the relationship between memory and speaking rate, sentence-level speaking rate would be more highly correlated with memory than would word- or syllable-level speaking rate.

This chapter describes an experiment designed to explore the speaking rate changes of pediatric CI recipients and TH participants for phonetically, lexically, and syntactically manipulated stimuli. In addition, the results of correlations between the speaking rates for these stimuli and participants' digit spans are presented.

Participants

Study participants were 10 children with CIs and 10 age-matched children with TH. The criteria for participants with CIs were the following: between 13 and 18 years old, implanted before or at five years old, no other known disabilities, in an oral language education setting, and with English as their first language. The participants with CIs were introduced to this study when they came to the University of Texas at Dallas Callier Center clinic to participate in other studies or to receive various services from clinicians. The Woodcock-Johnson III Tests of Achievement (Dean, 2011), a reading fluency subtest, was used as a reading test to make sure that they could read the stimuli. Their average reading age equivalent was 14.18 years (*SD*=4.04; range = 8-18).

Members of the TH (control) group were age-matched to the CI group, have no reported speech, language, or hearing problems, and speak English as their first language. Participants with TH were recruited from the greater Dallas/Fort Worth community through fliers and by word of mouth. Prior to testing, participants with CIs and TH and their parents signed consent forms which were approved by the University of Texas at Dallas Institutional Review Board. Both assent and consent were obtained. The average age of the ten teenager participants with CIs was 15.3 years old (*SD*= 1.8) and the average AoI was 21 months (*SD* =10). Seven participants with CIs were female and three were male. For the control group, the average age was 14.8 years old (*SD*= 1.6). Two participants with TH were female and eight were male.

Procedure

Stimuli: speaking rate data were collected using syllable, word, and sentence repetition tasks (Appendix B). When the participants repeat syllables, lexical retrieval and syntactic processing stages are assumed to be bypassed in the speech production process (Levelt, 1992). Similarly, repeating words does not require syntactic organization, while sentence repetitions arguably involve all stages (phonological, lexical, and syntactic).

For the phonetic level (syllable) condition, four strings of 10 syllable nonsense utterances (e.g., *jachava zatha vazatha chavaza*) were used. Syllable stimuli were composed of high phonemic similarity and low phonotactic probability strings to place additional demands on the phonological planning level and articulation. Based on pilot testing, it was found that grouping the nonsense syllables into polysyllabic segments appeared more reliable across talkers than using a series of individual nonsense syllables.

Stimuli for the lexical level (word) condition consisted of four words (e.g., "*musician tulip gorilla cement"*). There were six strings of words from low frequency and late age of acquisition (AoA) word lists, extracted from a 30,000-word database to place additional demands on lexical retrieval (Bird, Franklin, & Howard, 2001; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012). In a string, two words were three syllables and the other words were two syllables, so one string had 10 syllables.

Syntactic level (sentence) stimuli consisted of six center-embedded sentences with 10-12 syllables (e.g., "*The small child that he fought for is doing fine*."). Some of these target sentences were adopted from the sentence list of Silverman and Ratner (1997), and some were created by researchers using high frequency words from the same database, used for lexical level stimuli. A brief description of the targets can be found in Table 4.1.

Table 4.1. *Stimuli characteristics, including level of grammar (phonetic, lexical, syntactic), stimuli information, and examples.*

Conditions	**Level of Grammar**			**Stimuli Information**	**Examples**
	Phonetic processing	Lexical retrieval	Syntactic organization		
1. phonetic-syllables	**V**			High phonemic similarity and low phonotactic probability	*jachava zatha vazatha chavaza*
2. lexical - words	**V**	**V**		Later AoA, low frequency words	*musician tulip gorilla cement*
3. syntactic-sentences	**V**	**V**	V	Center embedded sentences	*"The small child that he fought for is doing fine."*

Data collection: Participants were tested individually in a quiet room. The participant was seated, facing a laptop computer monitor. Next, the participant received instructions given in an oral presentation and then viewed written sentences on the screen. All stimuli were pre-recorded in a sound booth by a male speaker of American English and were presented to the participant in audio and written form to decrease working memory load. The average modeled speaking rates were 2.5 syll/sec (*SD*=0.2) for the phonetic condition, 3.1 syll/sec (*SD*=0.2) for the lexical condition, and 3.7 syll/sec (*SD*=0.2) for the syntactic condition. Participants saw one stimulus per presentation page and were instructed after playing an audio file to repeat the utterances "using a comfortable rate of speech, as if talking to a friend." For Experiment 2, the entire session takes approximately 10 minutes. The order of presentation of stimuli was pseudo-randomized within conditions. When a participant made self-corrections or speech errors such as repetition, interjection, or a deletion of sounds or words, the tester encouraged the participant to repeat the stimulus one more time. In this case, we used the second attempt for speaking rate analysis. Participants' responses were recorded using a portable audio recorder, and the total duration of each stimulus production was measured using acoustic analysis software (*Praat*, Version 6.0.23) (Boersma, 2002).

Digit Span: Participants repeated a list of digits, forwards and backwards, using the WISC - III digit span memory task (Wechsler, 1991). A test administrator demonstrated digits to the participants at a rate of approximately one digit per second (WISC-III Manual, Wechsler, 1991). Participants were required to repeat the digit list (digits-forward) or to reverse the order (digits-backward). The digit list starts with two numbers and adds one more on successful repetition until a participant reproduces two series of digits incorrectly. There was a maximum of eight numbers for the digits-forward test and a maximum of seven numbers for the digits-backward test. For each level of number of digits, there are two series of number strings to try. According to the manual, one point was given per correctly repeated attempt so the maximum possible points for the digits-forward test was 16 (8 digits x 2 tries) and the maximum points for the digits-backward test was 14 (7 digits x 2 tries) (WISC-III Manual, Wechsler, 1991)[1]. Sum of raw scores of digits-forward and digits-backward served as a total digit span score for this dissertation.

Method of analysis

Data Analysis: To analyze the speaking rate differences between the CI and the TH groups on different linguistic levels, a mixed-design (Group x Linguistic level) repeated measures analysis of variance (ANOVA) was performed with speaking rate (syll/sec) as the dependent variable. The main effects of group and linguistic level, as well as an interaction between them were evaluated at the level of $p<0.05$. If there was a main effect of the linguistic level, post-hoc analysis corrected by Bonferroni method was performed to determine where the difference is. Univariate ANOVA was also performed to compare speaking rate differences between the CI group and the TH group at each level of the conditions. The correlations between speaking rates at different linguistic levels and digit span were analyzed to explore the relationship between speaking rate and memory at different linguistic levels.

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[1] Note, some clinicians and researchers use a more intuitive scoring of the digit span by stating the longest span recalled. For example, when a participant successfully repeated the strings of five digit is described as score “5” not “10” as instructed by WISC- III. However, the scoring method recommended by WISC- III accounts for single missing levels and therefore is more precise.

Results

Average speaking rates (syll/sec) and *SD*s of the CI group (n=10) and TH group (n=10) are presented in Table 4.2. for the phonetic, lexical, and syntactic level stimuli. Visual inspection of the data indicated both groups showed the slowest speaking rate at the phonetic level. The CI group showed similar speaking rates for the lexical and the syntactic levels, while the TH group showed a faster speaking rate for the syntactic level compared to the lexical level. Individual speaking rates for the CI group and the TH group are displayed in Figure 4.1. With the exception of participants CI07 and CI10, who showed lexical and syntactic level differences, all other participants with CIs showed similar speaking rates for the syntactic and lexical levels.

Table 4.2. *Speaking rate (syll/sec) of the CI and TH groups (n=20) for phonetic, lexical, and syntactic level stimuli*

	Group					
	CI		TH		All	
Condition	Mean	SD	Mean	SD	Mean	SD
Phonetic	2.63	0.47	2.66	0.32	2.65	0.68
Lexical	3.23	0.65	3.57	.0.25	3.40	0.66
Syntactic	3.22	0.86	4.11	0.35	3.66	0.85
All	3.03	0.71	3.45	0.67	3.24	0.72

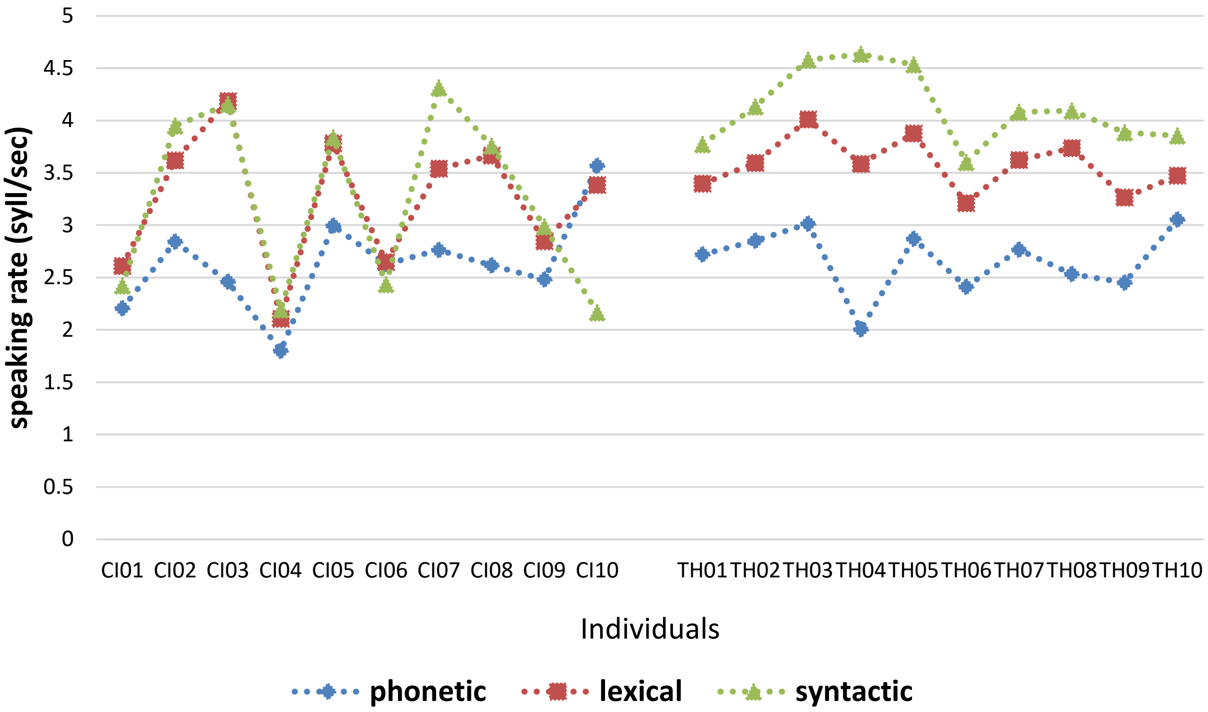

Figure 4.1. Individual speaking rates of CI talkers *(n=10)* (left side) and TH talkers *(n=10)* (right side) for linguistic levels

The collected data were further analyzed using a mixed-design repeated measures ANOVA with a within-subjects factor of stimuli (phonetic, lexical, syntactic) and a between-subjects factor of group (CI group, TH group). Mauchly's test showed that the assumption of sphericity had been violated ($\chi^2(2) = 19.2$, $p < 0.05$). Thus, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.59$).

The ANOVA showed significant main effects for group ($F(1, 18) = 4.85$, $p < 0.05$, $\eta p^2 = 0.21$) and linguistic levels ($F(1.2, 21.4) = 37.74$, $p < 0.05$, $\eta p^2 = 0.67$) on speaking rate (Table 4.3.). A main effect of group showed that speaking rate of participants with CIs was slower than speaking rate of participants with TH. A main effect of linguistic levels indicated that some speaking rates measured at three different linguistic levels differ significantly. Pairwise analysis adjusted by Bonferroni correction for multiple comparisons showed that the differences existed between speaking rates measured at phonetic and lexical levels (p<0.05, d= 1.65), phonetic and syntactic levels (p<0.05, d=1.62), and lexical and syntactic levels (p<0.05, d=0.39). There was a significant interaction between group and linguistic levels, indicating that groups reacted differently to the linguistic levels, $F(1.2, 21.4) = 6.48$, $p < 0.05$, $\eta p^2 = 0.27$. Post-hoc pairwise analysis for each group with Bonferroni correction for multiple comparisons showed that the speaking rate was similar at the lexical level and the syntactic level for the CI group (p=0.22), while the speaking rate was significantly slower at the lexical level than the syntactic level for the TH group (p<0.05, d=0.48), confirming the descriptive analysis (Figure 4.2.). In addition, the univariate ANOVA showed that the speaking rate difference between the CI group and the TH group occurred only at the syntactic level, $F(1, 18) = 9.129$, $p<0.05$, $\eta p^2 = 0.34$, suggesting that slowed speaking rate of the CI group occurred at the syntactic level.

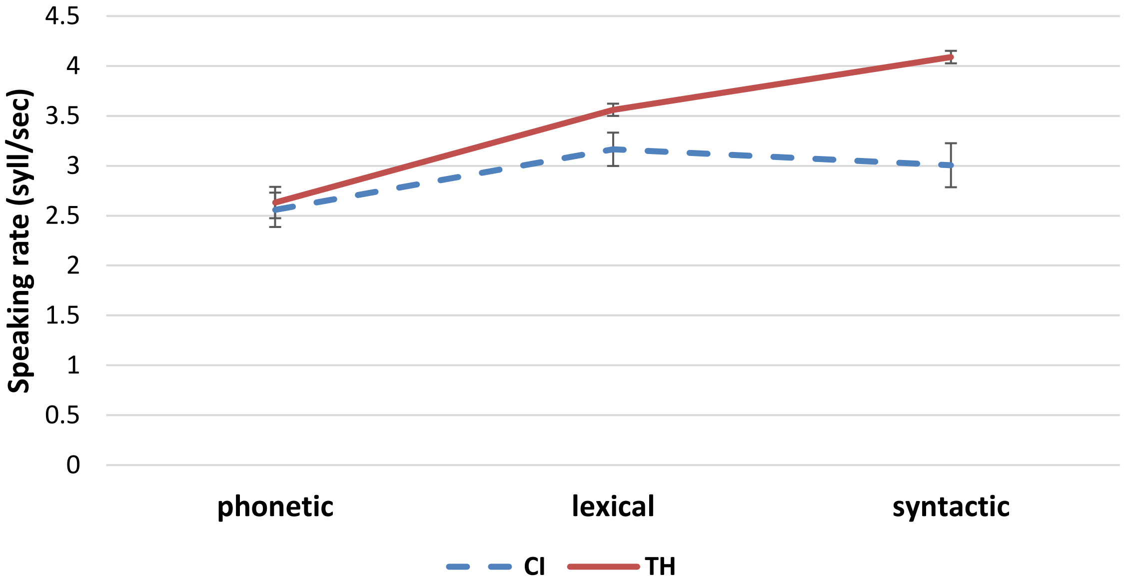

Figure 4.2. Average speaking rate of CI talkers *(n=10)* (solid line) and TH talkers *(n=10)* (dashed line) for linguistic levels, with standard error bars included

Table 4.3. *Summary of mixed-design repeated measures ANOVA for Experiment 2*

	Sum of Squares	df	Mean Square	F	p-value	Partial Eta Squared
Between Groups	2.66	1	2.66	4.85	0.04*	0.21
Within Groups	11.17	1.19	9.37	37.73	0.00**	0.67
Interaction	1.91	1.19	1.61	6.48	0.02*	0.27

**p<0.01, *p < 0.05

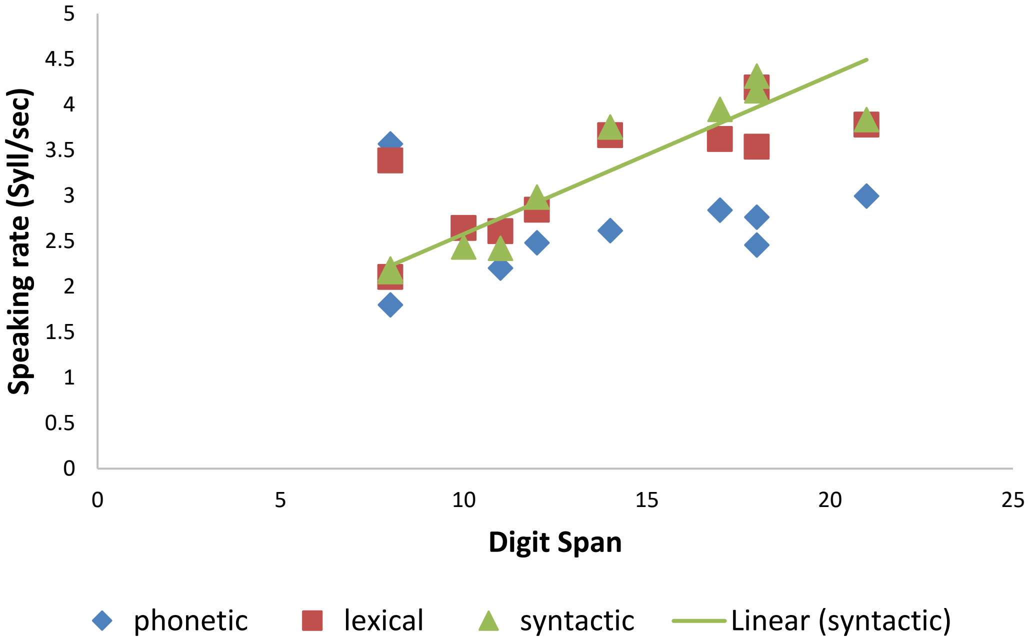

Figure 4.3. Scatter plot between digit span scores and speaking rate for phonetic (rhombus), lexical (square), and syntactic (triangle) conditions of CI talkers *(n=10)* with regression fit for the strongest correlation (SR at syntactic condition and digit span) is shown

Figure 4.3. displays a scatterplot between digit span and speaking rate measured by phonetic, lexical, and syntactic level stimuli for 10 teenagers with CIs. The average digits forward score was 7.7 (*SD*=3.12, *Z*-score=-1.15, 12.4 percentile) and the average digits backward score was 6 (*SD*=1.76, *Z*-score=-1.18, 11.9 percentile). Digit span scores were significantly correlated with speaking rate for syntactic-level stimuli ($F(1,9)=56.51$, $R^2 = 0.86$, $p < 0.05$) and lexical-level stimuli ($F(1,9)=15.75$, $R^2 = 0.64$, $p < 0.05$) but the correlation between digit span and speaking rate at the phonetic level stimuli was not significant ($F(1,9)=0.79$, $R^2 = 0.08$, $p = 0.36$) (Figure 4.3.). These results demonstrate that better STM was associated with faster speaking rate when the CI group repeated words and sentences, but not syllables. The strongest correlation was between speaking rate for syntactic level stimuli and digit span ($R^2 = 0.86$), suggesting that the speed and efficiency of syntactic processing might be a key factor in the relationship between STM and speaking rate.

In summary, the results of Experiment 2 suggest that syntactic processing is a contributing factor for the slowed speaking rate of CI recipients. Results also suggest that slowed syntactic processing may influence the relationship between speaking rate and the STM of children with CIs.

CHAPTER 5

EXPERIMENT 3. ROLE OF PARALINGUISTIC FACTORS

For everyday speech in TH individuals, speaking rate is influenced not only by cognitive/linguistic factors (examined in Chapters 3 and 4), but also by paralinguistic factors. People voluntarily change their speaking rate to speak clearly (Longhurst & Siegel, 1973; Picheny et al., 1986), to match their conversation partners’ speaking rate (Manson et al., 2013), or to respond to requests for rate changes (Tsao & Weismer, 1997). An important question is whether these paralinguistic factors are influencing the slowed speaking rate of children with CIs, as described in Chapters 3 and 4. One possibility is that the slowed speaking rates of CI recipients are affected by paralinguistic factors and that these individuals produce a slowed speaking rate as a compensatory strategy in order to produce clearer speech. An intact ability to control speaking rate in order to speak faster or slower would support this hypothesis. Another possibility is that CI recipients may have limited auditory feedback from a lack of auditory input, and this may be the reason for their slow speaking rates. If this is the case, CI recipients may have difficulty increasing or decreasing their speaking rates. However, the ability to control speaking rate has not been explored in either adults or children with hearing impairment. This chapter presents a study examining the role of paralinguistic factors in the speaking rate of children with CIs by requesting subjects to speak under different rate conditions (fast, habitual, and slow/clear). The performance of participants with CIs is compared with that of age-matched participants with TH.

Participants

Participant criteria were the same as experiment 2 in Chapter 4. Twelve teenagers with CIs (eight females and four males; average age is 14.9 years old (*SD* = 2.0); average AoI is 23 months (*SD* = 11 months)) and age-matched teenagers with TH (three females and nine males; average age = 14.9 years, (*SD* = 1.6)) participated in the third experiment. Out of 24 participants, 20 also participated in the second experiment. Four of the current 24 children did not participate in the second experiment for the procedural reasons.

Procedure

Stimuli: Speech materials included eight sentences. Each sentence was controlled for length (10-13 syllables) and semantic content (6-7 words chosen from the high frequency words list of the American Heritage Institute (AHI)) (Carroll, Davies, & Richman, 1971) (Appendix C). Participants repeated target sentences at three different rates, using recorded and written stimuli. As noted previously, modeled speech was produced by a single, male native speaker of American English. The average speaking rate for recorded model speech was 3.3 syll/sec (*SD*=0.3). The instruction for the habitual rate was the same as Experiment 2: “using a comfortable rate of speech, as if talking to a friend.” For the fast speaking rate condition, subjects were instructed to repeat the sentences “as fast as you can” without making the speech unintelligible. For the clear and slow condition, participants were instructed to “repeat the sentences clearly and slowly so the listener can understand you better.” No models for speeding up or slowing down were given. Participants’ responses were recorded and analyzed using *Praat* (Version 6.0.23) (Boersma, 2002).

Method of analysis

Data Analysis: To analyze the speaking rate changes when speakers were requested to speak fast, habitual, and clear/slow for the CI and TH groups, a mixed-design (Group x Rate) repeated measures analysis of variance (ANOVA) was used, with speaking rate (syll/sec) as the dependent variable. The main effect of group and rate conditions, and the interaction between them were analyzed at the level of $p<0.05$. Post-hoc (pairwise) analyses corrected by Bonferroni were performed to determine the differences between the rate conditions. In order to determine whether each group (CI group and TH group) changed their speaking rate significantly upon the request to speak fast, habitual, and slow/clear, one-way repeated measures ANOVAs were performed on each group with post hoc analyses corrected by Bonferroni correction.

Results

The average speaking rates and SDs of the CI group (n=12) and the TH group (n=12) are displayed in Table 5.1. by fast, habitual, and clear/slow conditions. Visual inspection of the data showed overall smaller speaking rate changes from the habitual condition to both the fast and the clear/slow conditions for the CI group, compared to the TH group. Data for individual subjects showed two outliers in the CI group, who slowed down their speaking rates from the habitual condition to the clear/slow condition as much as the individuals in the TH group (CI02, CI04), while other participants with CIs showed similar speaking rates for the habitual condition and the clear/slow condition (Figure 5.1).

Table 5.1. *Speaking rate (syll/sec) of the CI and TH groups (n=24) for fast, habitual, clear/slow conditions*

	Group					
	CI		TH		All	
Condition	Mean	SD	Mean	SD	Mean	SD
Fast	5.50	1.13	6.54	1.16	6.02	1.15
Habitual	4.26	0.89	4.62	0.53	4.44	0.72
Clear/slow	3.97	0.82	3.96	0.42	3.97	0.42
All	4.58	0.95	5.42	0.70	4.80	1.26

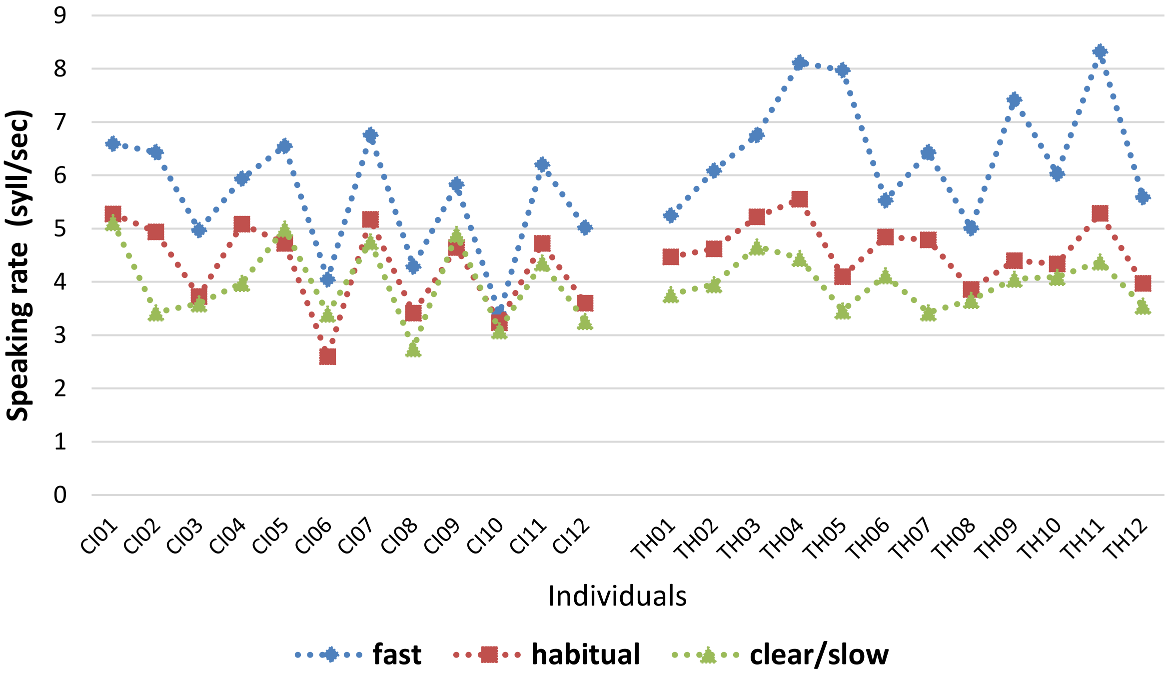

Figure 5.1. Individual speaking rates of CI talkers *(n=12)* (left side) and TH talkers *(n=12)* (right side) for different rate conditions

A mixed-design repeated measures ANOVA was performed to find the main effects of group and condition and an interaction. The collected data did not meet Mauchly's test of sphericity ($\chi^2(2) = 9.59$, $p < 0.05$) so the Greenhouse-Geisser correction was used ($\varepsilon = 0.73$). Speaking rate was not significantly different between participants with CIs and participants with TH, $F(1,22) = 2.24$, $p = 0.14$, $\eta p^2 = .09$. However, there was a significant interaction between group (CI and TH) and rate conditions (fast, habitual, and slow/clear), $F(2.44) = 3.470$, $p < 0.05$, $\eta p^2 = 0.22$, indicating the CI group changed their speaking rate differently than the TH group. There was a significant main effect of speaking rate conditions, $F(1.4, 32.9) = 100.24$, $p < 0.01$, $\eta p^2 = 0.82$. A pairwise comparison adjusted by Bonferroni demonstrated that overall speaking rate in the fast condition was significantly faster than the habitual condition ($p<0.05$) and the slow/clear condition ($p<0.05$), and the habitual condition was significantly faster than the slow/clear condition ($p<0.05$) (Figure 5.2.).

One-way repeated measures ANOVA and pairwise analyses were used to find out if participants in each group were able to significantly speed up or slow down. In the CI group, speaking rate changes by the conditions were significantly different, $F(2,22) = 44.72$, $p<0.05$, $\eta p^2 = 0.80$. Post-hoc tests using Bonferroni correction revealed that speaking rates were significantly different between the fast and habitual conditions ($p<0.05$. $d=1.21$) but speaking rates between the habitual and slow/clear conditions were not significantly different ($p=0.38$, $d=0.35$). In the TH group, speaking rate changes by rate condition were significantly different using a one-way repeated measures ANOVA with Greenhouse-Geisser correction, $F(1.15, 12.72) = 57.15$, $p<0.05$, $\eta p^2 = 0.84$. Post-hoc testing using the Bonferroni correction revealed that speaking rates differed between the fast and habitual conditions ($p<0.05$. $d=2.10$) and between the habitual and clear/slow conditions (*p*<0.05, *d*=1.39). These results suggest participants with CIs changed their speaking rate significantly faster in the fast condition than the habitual condition but failed to slow down for the slow/clear condition compared to the habitual condition. Participants with TH were able to change their speaking rate significantly for both the fast and slow/clear conditions.

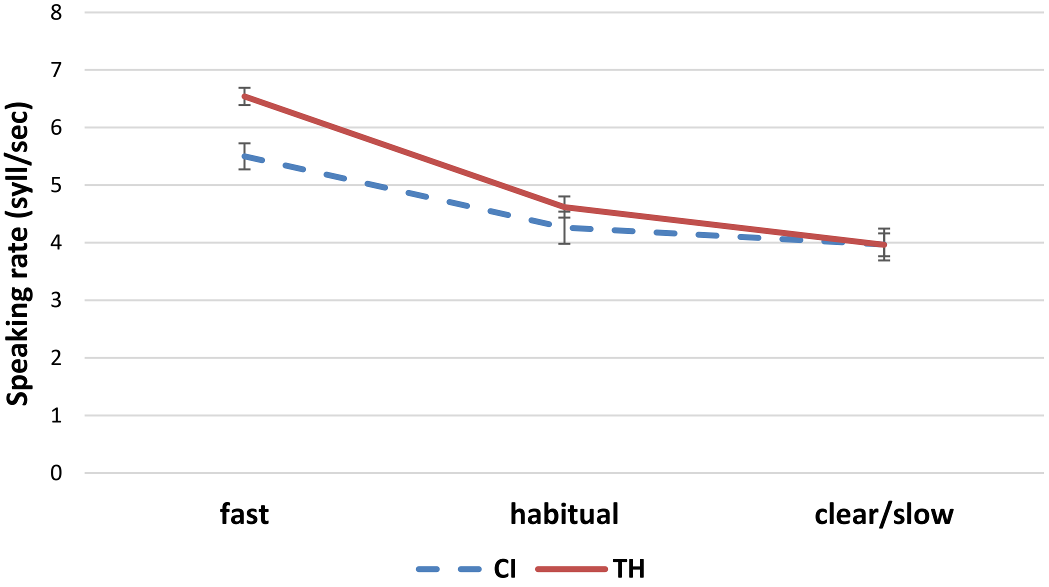

Figure 5.2. Average speaking rate of talkers with CIs *(n= 12)* (solid line) and talkers with TH *(n=12)* (dashed line) with standard error bars indicated. Fast, habitual, and clear/slow rate conditions are shown.

Table 5.2. *Summary of mixed-design repeated measures ANOVA for Experiment 3*

	Sum of Squares	df	Mean Square	F	*p*-value	Partial Eta Squared
Between Groups	3.89	1	3.894	2.24	0.15	0.09
Within Groups	55.54	1.40	37.96	100.24	0.00**	0.82
Interaction	3.38	1.40	2.31	6.09	0.01*	0.22

**p<0.01, *p < 0.05

CHAPTER 6

GENERAL DISCUSSION

In this dissertation's first experiment (using data from an existing dataset) we examined longitudinal relationships between chronological factors (chronological age, hearing age, duration of deafness, and age of implantation) and speaking rate, and performance variables (speech perception, speech intelligibility, and language) and speaking rate, measured at four to eight years after implantation. The data were analyzed longitudinally by following children with CIs and TH over five years.

Chronological factors on the speaking rate of CI users

Results of Experiment 1 are in general agreement with previous studies of the speaking rate of CI and TH participants (Chuang et al., 2012; Geers, Pisoni, & Brenner, 2013; Perrin et al., 1999), showing that the speaking rates of participants with CIs are significantly slower than age-matched TH peers at 4, 5, 6, 7, and 8 years after implantation. The current results expand upon previous reported results by finding that the children with CIs do not necessarily "catch up" to their peers or show a ceiling effect, even after eight years of CI use. These findings support the hypothesis that children with CIs will produce slower speaking rate because of unstable internal models caused by defective auditory input (Perkell et al., 2000).

As expected, the speaking rate of children with CIs became significantly faster over time with a longer duration of CI use (hearing age). Thus, the longer participants had hearing experience with CIs, the faster they spoke the target sentences. This result suggests that amount of hearing experience influences speaking rate. The present study's findings are similar to the findings reported in previous studies and expand upon these reports by describing speaking rates every year from four to eight years after implantation (Evans & Deliyski, 2007; Kishon-Rabin et al., 1999).

Chronological age (CA) was also significantly related to the speaking rate of children with CIs, even after four to eight years post-implantation. Thus, the older the participants, the faster the measured speaking rate. Previous studies have shown mixed results concerning the effects of CA on other speech and language outcomes. Some studies have reported that speech and language outcomes improve with CA, while others found that only hearing age (duration of CI experience) is related to speech and language outcomes, not CA (Huang et al., 2005; Phillips et al., 2009). In the present study, both CA and hearing age were significantly related to the speaking rate of the CI group, although the linear mixed-effects model tested with hearing age showed a significantly better fit than the model tested with CA. These findings match the hypothesis that hearing experience and physical and cognitive maturation are both important for building and maintaining the internal model for speech production (Perkell et al., 1997; Perkell et al., 2000).

Age of implantation (AoI) and the duration of deafness were previously reported to be an important factor that affects various outcomes, including speech perception (Sharma et al., 2002; Svirsky, Teoh, & Neuburger, 2004), speech production (Tobey et al., 2013), and language (Niparko et al., 2010). However, the relationship between AoI (or duration of deafness) and speaking rate have not been previously reported. The present study examined whether AoI and duration of deafness can predict speaking rates, which were measured at four to eight years after implantation. Surprisingly, in the present results both AoI and duration of deafness were not significantly related to speaking rate development at any point between four and eight years of

CI experience. One potential reason is that AoI and duration of deafness are not as powerful factors in building and maintaining the internal model as are hearing age or CA. Another explanation for this difference is that a five year follow-up was not long enough to see the effects of early implantation. Results of Experiment 1 show that the earlier implanted children with CIs did not begin to improve their speaking rate until seven years after implantation, so earlier implantation is not advantageous for speaking rate development when the duration of CI experience is less than seven years (Figure 3.6.). The data suggest that children who receive CI at a young age have a different pattern and time frame for speaking rate development than do children who receive CI when they are older.

Another possible explanation for no effect of AoI and duration of deafness on SR could be the range of AoI. In Experiment 1, all of the participants received CIs before age five. If this experiment had allowed enrollment of participants with a greater range of AoI and duration of deafness, the effect of AoI and duration of deafness may have been important factors. In addition, this null finding could be because the participants were too old to register an effect of AoI and duration of deafness. Researchers may yet find significant AoI and duration effects on SR if SR is analyzed for younger participants whose ages are four to six years.

Performance variables on the speaking rate of CI users

We analyzed the relation between the speaking rate of the CI recipients and their performance scores, including speech perception, SI scores, and language at 4, 5, 6, 7, and 8 years after implantation. Previously, studies have reported a significant relation between speech perception and speaking rate (Pisoni et al., 2003), SI and speaking rate (Tobey et al., 2003;

Uchanski, & Geers, 2003), and language and speaking rate (Geers & Sedey, 2011) of CI recipients. In the current data, speech perception scores of children with CIs were significantly related to speaking rate development at 4, 5, 6, 7, and 8 years after implantation. Although the relationship was statistically significant, the speaking rate prediction from speech perception scores was not as strong as the prediction models from SI and language scores. One possible reason for this result is a ceiling effect of speech perception scores. In our data, over 85% of participants reached ceiling at eight years after implantation. One way to potentially reduce the ceiling effect is to extend the speech perception index to include more advanced tests (e.g., HINT tested in noise). Another way of analyzing the data that avoids the ceiling effect is to use earlier speech perception data to predict later speaking rate scores. When speech perception data at four years after implantation was used to predict speaking rate at 4, 5, 6, 7, and 8 years after implantation, the model significantly predicted speaking rate. In addition, the model with earlier speech perception scores as a fixed effect showed a significantly better fit to predict speaking rate than when speech perception scores at every visit were used as a fixed effect. Better speaking rate prediction with earlier speech perception can be understood by a ceiling effect (i.e., a greater range for linear mixed-effects model). Another possible explanation is that speech perception skills acquired at an earlier age are more important for building and maintaining the internal models than speech perception measured at later ages.

As expected, the SI scores of the CI recipients were significantly related to overall speaking rate development 4, 5, 6, 7, and 8 years after implantation. Thus, the faster children with CIs talk, the better listeners are able to understand their speech. A question arises about the direction of this relationship; either speaking rate influences SI, SI impacts speaking rate, or both factors are associated with gradually improving speech production skills in this population. Current results of Experiment 1 show that SI improved first around six years after implantation; then, speaking rate improved around seven and eight years after implantation (Figure 3.9.). We may speculate that children with CIs improve speech intelligibility early. Next, with better speech production and more confidence in speaking, they start to develop the ability to speak faster.

It is important to note that the relationship observed between speaking rate and SI was found to be very similar in the data of the age-matched TH group. speaking rate development was significantly related to SI at the 4, 5, 6, 7, and 8 year follow-ups, and SI improved at the six-year follow-up, followed by faster speaking rate at the seven and eight-year follow-ups. This suggests that better SI is associated with faster speaking rate regardless of whether participants had CI or TH.

Although few researchers have focused on the relation between language and speaking rate, we found a strong association between language and speaking rate that persisted over time. This may suggest that the slowed speaking rate of CI recipients is influenced by weaker language skills and slower language processing, also explored in Experiment 2. One possible explanation for this consistently strong correlation several years after implantation is that both language skills and speaking rate are influenced by syntactic knowledge, lexical information, and phonological processing. The present study (Experiment 1) compared overall language scores measured by a standardized battery, CASL (Carrow-Woolfolk, 1999), with speaking rate in CI and TH children. In the future, we plan to compare individual subset scores on the CASL battery with speaking rate to further determine if syntactic, semantic, or pragmatic knowledge play a unique role in the relation between language and speaking rate.

Role of language processing

Experiment 2 explored the relation between speech production processing and the slowed speaking rate in CI recipients by comparing speaking rates between CI and TH groups in the context of differing linguistic demands (phonetic, lexical, and syntactic). Stimuli were created to produce processing demands focused on each linguistic level. Consonants with high phonemic similarity and low phonotactic probability were used in non-word syllable strings for the "phonetic level" stimuli, later age of acquisition and low frequency words were used for the "lexical level" stimuli, and center-embedded sentences were used for the "syntactic level" stimuli. All the stimuli were controlled to have similar length and metrical structure. Results showed that the speaking rates for phonetic level (syllable-nonword) stimuli and lexical-level (word) stimuli did not differ between the CI group and the TH groups. However, participants with CIs produced much slower speaking rates for syntactic-level (sentence) stimuli than participants with TH. These findings suggest that the slowed speaking rate in CI recipients relative to their TH age-mates is primarily related to syntactic-level processing.

In previous studies, researchers have suggested the speed and efficiency of articulation (Kent & Forner, 1980; Smith & Goffman, 1998) and/or lexical representation and encoding (Green et al., 2000; Laganaro et al., 2012; Moore & Maassen, 2004) underlie the speech rate of populations. However, the findings of the current research project do not support these previous claims for the TH group, instead suggesting that syntactic-level processing most highly relates to the slowed speech of CI recipients.

Several possible interpretations can be applied to the results of the current study. First, participants with CIs may have shown slowed speaking rate, particularly in terms of syntactic-level processing, because of their limited grammatical ability compared to participants with TH. Previous research has reported that more than half of children with CIs are behind in receptive and expressive language, compared with their age-matched peers (Geers, Moog, Biedenstein, Brenner, & Hayes, 2009). This interpretation also corresponds to findings from Experiment 1, which showed that language ability was significantly related to speaking rate development at four to eight years after implantation. Indeed, language score was a stronger predictor of speaking rate than any of the other factors examined, such as SI or speech perception. In the second experiment, producing phonetic-level (e.g. *jachava zatha vazatha chavaza*) and lexical-level stimuli (e.g. *musician tulip gorilla cement*) did not require processing of syntax and morphology. Thus, slowed speaking rate at a syntactic level can be understood by reduced linguistic ability, including grammatical knowledge, in the CI population.

Another interpretation is grounded in the concept of "accumulated demands." If one adopts Levelt's (1992) speaking model, repeating sentences requires four levels of processing (articulation, phonological processing, lexical retrieval, and syntactic processing), repeating words requires three levels (articulation, phonological processing, and lexical retrieval), while repeating non-word syllables requires only two levels (articulation and phonological processing). Thus, participants with CIs may have had the most difficulty responding to syntactic-level stimuli as such stimuli required them to process at all processing levels. A future study might test this explanation by examining speaking rate changes with more modules involved, such as stimuli requiring further semantic or pragmatic processing.

Still another interpretation of the present study's results relies on the concepts of prosody and intonation. Producing sentence-level stimuli requires participants to use more prosodic and intonation demands than when repeating syllable- or word-level stimuli. Slowed speaking rate at the sentence level in participants with CIs may thus have been related to their limited prosodic and intonation abilities which are required for fluent sentence speaking.

Short-term memory (STM) and the speaking rate of CI users

The relation between digit span (memory) and speaking rate was not significant at the phonetic level stimuli while it was at the lexical and syntactic levels. The results also indicated that the strongest relationship was between speaking rate at the syntactic level stimuli and digit span. This result supports the claim that syntactic-level processing is (1) a critical cause of slowed speech in participants with CIs and is (2) closely related to their memory ability. One interesting point is that the digit span scores of participants with TH were not related to their speaking rate at any level. This suggests that the relation between speaking rate and memory may be only apparent for the population that has language, memory, and speaking rate difficulties.

This significant relation between memory and speaking rate of participants with CIs is not well explained by phonological loop theory. If the relation between memory and speaking rate were only based on phonological loop theory, in which verbal rehearsal speed determines how much memory is stored in the loop, speaking rates at all the levels should be related to digit span for both the CI group and the TH group. In particular, this theory does not explain how the relation between speaking rate at the sentence level and digit span is stronger than the relation between speaking rates at the word-level or syllable-level and digit span. A limited cognitive processing speed of CI recipients may explain these STM results. Previous studies suggested an effect of limited and slowed processing speed on speech perception and production in various populations, such as children with attention-deficit hyperactivity disorder (ADHD) (Carte, Nigg,

& Hinshaw, 1996), elderly individuals (Caplan & Waters, 2005), and bilingual speakers (Van Gelderen et al., 2004). In addition, CI recipients are reported to have difficulties with executive functions such as inhibition and concept formation (AuBuchon et al., 2015; Marschark et al., 2017). Several studies have connected processing speed and WM (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Fry & Hale, 1996; Luciano et al., 2001). Another attribute of limited cognitive processing speed is that it may have very particular effects on performance, affecting one specific behavior and not others based on domain specificity of processing speed (Kail, 1991; Kail & Miller, 2006). Based on these studies, it is possible that limited cognitive processing speed of CI recipients underlies the slow speaking rate for sentence level stimuli and also for reduced STM (measured by digit span).

Role of paralinguistic factors

Experiment 3 explored whether participants with CIs are able to change their speaking rate voluntarily and whether paralinguistic abilities are related to their slowed speaking rate. The researchers asked participants with CIs and participants with TH to produce eight sentences in fast, habitual, and clear/slow conditions. Target sentences were controlled for length (10-12 syllables) and semantic context (all were high frequency words). A mixed-design repeated measures ANOVA revealed a significant interaction as well as a main effect of rate conditions. The statistically significant interaction demonstrates that the groups (CI /TH) reacted differently to the rate conditions. A one-way repeated measures ANOVA was performed to find out how each group reacted to fast, habitual, and slow/clear conditions. It was found that the CI group was significantly able to speed up for the fast condition but could not significantly slow down for the slow/clear condition, while the TH group was able to speed up and slow down significantly.

There could be several interpretations for these group differences. First, the CI group was able to significantly increase speaking rate and also produced speech in the fast condition as fast as or faster than their counterparts' habitual condition. This suggests that the CI recipients' slowed speech may have been due to strategic choices since they were able to speak as fast as their counterparts upon request.

On the other hand, the finding that participants with CIs could not significantly slow down can be understood in at least two ways. One possible explanation is their limited use of auditory feedback. According to previous kinematic research (Adams, Weismer, & Kent, 1993), lower lip and tongue movement velocity changes from a symmetrical, single-peaked function in fast speech to asymmetrical, multi-peak movements in slow speech, suggesting that this control is influenced by auditory feedback. Thus, CI recipients may not have slowed down their speaking rate successfully because they could not use auditory feedback as well as their counterparts.

A second potential explanation is that the participants with CIs already produced compensatory slowing in their habitual condition and thus show less change with the slow and clear condition. That is, when participants with CIs were asked to speak habitually, they were already adopting a compensatory slowing strategy and thus produced comparable speaking rate to their counterparts' performance in the slow and clear condition. Therefore, the change between habitual and "slow and clear" would not be expected to be very large. Further research is required to investigate whether and how participants with CIs use strategic slowing when they are speaking naturally and to determine why CI recipients may differ in this respect from their counterparts.

It is also important to note that the failure to find a statistically significant difference between speaking rates at habitual condition and slow/clear condition could be because of a small effect size and a small number of participants. Accordingly, the results of Experiment 3 should be replicated with a larger number of participants.

Limitations and future research

A strength of Experiment 1 is the use of a large, pre-existing longitudinal dataset in order to address the speaking rate of a well-sampled group of children with CIs and an age-matched control group with TH. These data were obtained from a multi-center project in the U.S. and across a five-year period to reveal long-term changes after implantation (i.e., four to eight years post implant in the CI group).

A practical issue that arose in Experiment 1 is that some data points were missing. While the study included participants, who were tested in at least three out of five sessions, 25% of the data points were still missing. Some of the data were absent because of missed visits. Since these data were collected over five years, longitudinally, there were participants who missed visits for various reasons, such as moving to other states. Another reason for missing data was incomplete data collection because the participants were not able to repeat the whole stimuli. In our data, there were more missing data at the four-year follow-up (40%) than the later testing sessions (18-24%). It seems that it happened because at the four-year follow-up, young participants' speech production abilities were not enough to repeat sentences. In future research, careful participant selection and close communication to the participants and their parents may reduce the rate of missing data.

When collecting speaking rate data for Experiment 1, the test administrators did not provide explicit instruction about the level of speaking rate requested of participants. Rather, they simply asked the participants to repeat their speech. Therefore, this method posed the potential risk to copy modeled speech. While the speaking rates of the testers were not available at the time of this study, conducting a correlation study between the participants and their testers' rate of speech would be valuable in the future in order to determine whether or not CI participants were imitating the speaking rate of the test administrators. In addition, comparing speaking rates produced from the test administrators who were not blinded to the groups (CI vs. TH) would suggest whether testers produced different speaking rate models for each group. In future research, it would be preferable to standardize speaking rates given to the subjects to prevent such potential confounding.

By contrast with Experiment 1, Experiments 2 and 3 were prospective experimental studies with control groups. Experiment 2 manipulated variables to contrast specific levels of grammar in order to determine where slow processing would occur, and Experiment 3 examined internal model deficits and paralinguistic changes involved in the speaking rate of CI recipients. These studies gave flexibility to test participants, but also presented some limitations. Limitations include potential lack of generalization due to the small sample size, geographic limitations, and the small pool of participants. Most of the participants lived in the Dallas/Fort Worth area and used oral communication mode; thus, these participants may not represent a nationwide sample population. Current results should be therefore confirmed with larger samples with more diverse characteristics to determine if the findings in Experiment 2 and 3 are valid.

Experiment 2 is a novel study exploring speaking rate challenges for CI participants based on the syntactic, lexical, and phonetic levels of processing. In this study, speaking rate at the lexical level was measured by repeating strings of words. Although this is one way to measure lexical production speed, a more common method is naming pictures or objects. In this experiment, we used strings of words to match the length and rhythmic structure of other levels of stimuli. However, in the future, speaking rate for the lexical level of processing might be measured by naming objects in pictures to confirm the results of this study about the effect of lexical retrieval on speaking rate.

Another future suggestion is to add an additional control for the syntactic level. Results of Experiment 2 demonstrated relative difficulty in syntactic level processing for the CI group, compared to the TH group. In the current study, speaking rate measured at the syntactic level was assessed by having participants repeat center-embedded sentences. In the future, speaking rates of these center-embedded sentences can be compared with the speaking rates of other syntactically challenging sentences of various levels of difficulty (e.g., right embedded sentences, simple active declarative sentences and/or “wh” questions) (Silverman & Ratner, 1997). This would be expected to improve understanding of the effect of syntactic difficulty on the speaking rate of the CI group. Some evidence supporting the effect of syntactic complexity may be found by comparing the speaking rate data for the habitual condition of Experiment 3 with the speaking rate data for the syntactic condition of Experiment 2 (since the targets for both tasks were sentences). When they were visually inspected, a faster speaking rate was noted for the simple sentences of Experiment 3 compared to the center-embedded sentences of Experiment 2, and this may suggest the importance of syntactic complexity on speaking rate for children with

CIs. However, since the current sets of sentences were not designed to be matched for syllabic and metrical characteristics, future research is needed to confirm this observation.

In Experiment 3, participants with CIs and TH were asked to speak “as fast as possible” and “slowly and clearly” in order to explore the effect of paralinguistic factors on speaking rate. A possible future method to collect data can be to set up a scenario to change the speaking rate rather than upon direct request. For example, a researcher sets up a scenario in which the participant must hurry or asks the participants if they can repeat the sentences because the researcher could not understand it.

Another future plan for Experiment 3 is to perform acoustic analysis of faster and slower/clearer speech to examine if speech produced by the CI group shows typical fast or clear speech characteristics, such as changes in duration of pauses and vowels, articulation of final consonants, and loudness of the speech (Picheny et al., 1986). Moreover, the analysis of sound and pause duration will provide evidence to determine whether children with CIs produce prolonged sounds, longer inter-word pauses, or larger pause proportion, for which previous research has reported mixed results (Chuang et al., 2012; Liker et al., 2007; Neumeyer et al., 2010; Patil et al., 2010). In addition, examining speech intelligibility scores at different speed conditions will be informative. One explanation for the slowed speech of CI recipients is to allow listeners to understand better. Exploring intelligibility scores at faster, habitual, and slow/clear speech conditions will address whether any observed strategical slow-downs are successful.

Clinical Implications

This dissertation demonstrated a slower rate of speech for the CI group compared to the age-matched TH group. The data of Experiment 1 showed that the average speaking rate of the CI group at four years after implantation was comparable to the average speaking rate of the TH group at eight years follow-up. An exciting clinical implication of these results is that speaking rate may serve as a potential indicator for later speech, language, and even cognitive success of children with CIs. The finding of close relationships of speaking rate with speech intelligibility, language, and STM suggest that speaking rate measured at a younger age may predict the development of speech production, language, and memory measured at later years. This idea should be tested in future research, including studies of younger children.

In addition to the literature addressing the relationship between CI children's slowed speech and lowered SI, clinical studies also indicate that children with CIs cannot speak age-appropriately and show deficits in self-esteem, quality of friendships, and overall quality of life (Most, 2010; Warner-Czyz, Loy, Evans, Wetsel, & Tobey, 2015). Thus, one may assume that the slowed speech of children with CIs warrants clinical attention.

While there are scare data addressing the treatment of slowed speech for individuals with CIs, one recent paper has suggested that rate control interventions for dysarthric patents might be implemented as a possible treatment (Freeman & Pisoni, 2017). (Blanchet & Snyder, 2010)(Blanchet & Snyder, 2010)An example is to practice speaking at a targeted speed with verbal, auditory, or visual feedback (Blanchet & Snyder, 2010). In addition to rate control treatment, the results of this dissertation suggest other possible interventions for the slowed speech of children with CIs. First, intervention focusing on the development of linguistic knowledge may be beneficial for increasing the speaking rate of CI recipients. In the first experiment results, language scores best explained the speaking rate of children with CIs out of the performance variables tested. One possible explanation is that slowed speech of children with CIs results from limited grammatical knowledge. This explanation also matches with the results of the second experiment which showed the slowest speaking rate when processing stimuli that presented a challenge at the syntactic level. Based on the relationship between linguistic ability and speaking rate, intervention addressing grammatical knowledge may be helpful for improving speaking rate development. However, this hypothesis warrants further testing.

In addition, we speculate that intervention addressing cognitive processing may be advantageous to both speaking rate and STM of children with CIs. From the second experiment, we observed that STM was strongly related to the speaking rate measured at the sentence level, while it was not related to the speaking rate measured at the syllable level. One possible explanation is that slowed cognitive processing affected both STM and speaking rate. Evaluating cognitive processing speed of this population in the future will be informative to validate this hypothesis and may suggest the benefit of cognitive processing treatment on speaking rate and STM.

Lastly, treating paralinguistic factors might be useful for helping children with CIs attain age-appropriate speaking rates. The third experiment suggests that children with CIs may slow their speech as a strategic choice in order to speak more clearly. Although these findings must be considered tentative because of small effect sizes and should be replicated with future studies, the data nevertheless suggest that clinicians might address subjective issues in treatment, such as how children with CIs feel about their own speaking rate, and whether interlocutors (including clinicians) feel the need to speak slower with their patients.

CHAPTER 7

CONCLUSIONS

This dissertation reports three experiments designed to help understand the reasons for the slowed speech of pediatric CI recipients. Experiment 1 examined the effects of maturation and hearing experience (chronological factors) on the speaking rate of children with CIs, as well as linguistic ability, speech perception, and speech production abilities (performance variables). Experiment 2 explored whether certain levels of linguistic processing are related to the slowed speaking rate of CI recipients. Paralinguistic ability and strategic slowdown of speaking rate were explored as a possible reason for the speaking rate slowdown in Experiment 3.

In Experiment 1, the speaking rates of participants with CIs were found to be significantly slower than children with TH at four to eight years after implantation, suggesting an unstable internal model for speech production resulting from degraded auditory feedback. Hearing experience and physical maturation played important roles, and speech intelligibility and language ability were closely related to speaking rate development. Unexpectedly, age of implantation and duration of deafness were not significantly related to the speaking rate of children with CIs, when examined longitudinally. Considered together, these data do not support the benefit of early access to auditory input to build speech production internal models, at least with respect to speaking rate. Rather, hearing experience, overall maturation, and language ability appear to be more important than the notion of a sensitive period.

Experiment 2 explored different levels of speech production processing to determine if the slowed speech of participants with CIs results from impairment of all levels of speech production processing, or whether one specific level is most responsible. The results indicate that the speed and efficiency of syntactic processing, rather than phonological or lexical processing, contributed to the slowed speech of CI recipients and supported a selective degradation hypothesis. This is a potentially important finding because it draws connections between speaking rate and the cognitive and linguistic demands on CI recipients. When the relation between speaking rate and STM measured by digit span was analyzed, speaking rate for stimuli designed to tap the syntactic level had the strongest relation to memory ability. The results of the present research thus provide evidence suggesting that speech production in CI recipients is influenced by higher level linguistic abilities, and this may also be a key for understanding the previously-described speaking rate and STM relationship.

Experiment 3 investigated CI recipients' ability to change the rate of their speech upon request; the results suggest that participants with CIs can increase their speaking rate as much as their counterparts with TH, but they cannot decrease their speech in a similar fashion. Although these results are tentative and need to be replicated with a larger number of participants due to a small effect size and small number of participants tested, the findings nonetheless suggest that children with CIs may habitually speak slower than their counterparts with TH for strategic reasons.

In summary, speaking rate was slower for the CI group than the TH group across the three experiments. The CI group's speaking rate was related to CA and duration of CI experience, suggesting that physical maturation and hearing experience are important for speaking rate development. The speaking rate of children with CIs was significantly related to speech perception, SI, and language abilities, and language ability explained speaking rate the best out of these performance variables. Processing sentences is suggested as a potential reason for the slowed speaking rate of the CI group and also as a key factor for the speaking rate and memory relationship. The children with CIs were able to speed up, although slowing down was not statistically significant, suggesting that their slowed speaking rate is related to paralinguistic factors. Taken together, the results suggest the causes for slowed speech in children with CIs is multifactorial, including maturation, auditory feedback, and linguistic and paralinguistic abilities. These findings have potentially important implications for theories of speech production and for the clinical treatment of individuals with hearing impairment.

APPENDIX A

LIST OF STIMULI FOR EXPERIMENT 1

36 high and low context sentences with three, five, and seven syllables were used as stimuli for experiment 1 (McGarr, 1983). Key word is italicized.

High context sentences	**Low context sentences**
Three syllables	
Keep quiet.	*Feed* the dog.
Read the book.	*Have* a lot.
Come *with* me.	You *did* it.
The *dog* barks.	I *need* it.
Comb your *hair.*	Get the *cake.*
That's no *good.*	This is *his.*
Five syllables	
The *cat* chased the mouse.	They *will* come again.
My *name* is Nancy.	Is *that* the tall one?
Get your *coat* and hat.	Mother *has* the car.
Get your *ball* and bat.	Who wants *this* ice cream?
Did you brush your *teeth?*	It’s easy to *hear* her.
Is there no *more* milk. They *will* come again	He said he *could* go.
Seven syllables	
That *man* is not my father.	The *book* is on the table.
I *wish* I had a pony.	What *was* the name of that boy?
We have *food* for the picnic.	If it’s *cool,* I cannot go.
The flag is *red,* white, and blue.	Is the *fat* baby crying?
May I have a *piece* of cake.	It is nice on a *fall* day.
Can you dive in *deep* water?	We will go to the *beach* today.

APPENDIX B

LIST OF STIMULI FOR EXPERIMENT 2

1. Phonetic –syllable condition

Thasa zathasa zathasa thasa.
Shaza thashaza thashaza shaza.
Chava jachava jachava chava.
Zatha vazatha vazatha zatha.

2. Lexical – word condition

Musician tulip gorilla cement.
Parrot builder carnival minister.
Lilacs chipmunk pianist celery.
Crocodile trophy sparrow carpenter.
Ginger squirrel gardener buffalo.
Enemy lizard balcony camel.

3. Syntactic – sentence condition

The car that we drove behind moved very slowly.
The ball that the boy played with looked dirty.
The small child that he fought for is doing fine.
The dog that the girl laughed at licked his paw.
The class that she spoke about started last week.
The wedding that he cried during started at one.

APPENDIX C

LIST OF STIMULI FOR EXPERIMENT 3

A beautiful girl just bought the blue dress on sale.
Everyone looks at my purple shoes and green bag.
Her mother came home late from the birthday party.
A black dog and white cat are running here.
The fish and the dolphin swam in the ocean.
Three friends are studying together in the room.
His music made the husband and wife cry.
Two boys and their brothers were unhappy yesterday.

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BIOGRAPHICAL SKETCH

Sujin Shin is a PhD candidate in the Communication Sciences and Disorders program at The University of Texas at Dallas. After earning a master's degree in speech and language pathology from Yonsei University (Seoul, Korea), she worked in several clinical settings, mostly working with children with cochlear implants (CIs). While working as a speech language pathologist in Korea, she developed a passion for studying speech production in people with speech and hearing difficulties. In Korea, she worked on various projects such as the standardized Korean Boston Naming Test (2005), speech perception characteristics of CI users (2006), and grammatical development after CI (2007). At The University of Texas at Dallas, she worked with Dr. William Katz in the Speech Production Lab and also in the Dallas Cochlear Implant Lab, under the guidance of Drs. Tobey and Warner-Czyz. During her PhD training, she completed practicums at several sites, including at Oak Hill Academy (Dallas, Texas) and Northlake Elementary School (Garland, Texas). She also enjoys teaching and has teaching experience at the university level as a lecturer in Korea (Aural Rehabilitation, Multi-cultural Issues in Communication Disorders) and as a teaching assistant in the USA (Introduction to Communication Disorders, Speech Science, Phonetics, Child Development, and Articulation Disorders).

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Speech Language Pathologist, Speech Language Hearing Lab in Asan Medical Center (Seoul, Korea). 2006 - 2007.

Intern, Mapping assistant, Seoul National University Hospital (Seoul, Korea). 2005.

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Teaching and research experience

Teaching Assistant, several communication disorders classes, including Introduction to Communication Disorders, Phonetics, Communication Science, Research Ethics, Child Development, Articulation Disorders, Exceptional Children, Language and Literacy Development, Neural Basis of Communication, Hearing and Deafness. The University of Texas at Dallas. 2008-current

Lecturer, Aural Rehabilitation for Children and Adults with Hearing Impairment, Multi-cultural Issues in Communication Disorders. Woosong University (Daejeon, Korea). 2011.

Research Assistant, Standardized Korean Boston Naming Test in Yonsei University (Seoul, Korea). 2004 - 2005.

Peer-reviewed publications

Tobey, E. A., **Shin, S.**, Prashant, M. S., & Geers, A. (2011). Spoken word recognition in adolescent cochlear implant users during quiet and multi-speaker babble conditions. *Otology & neurotology*, *32*(3), 413-8.

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Shin, S., Shin, J., Yoon, M. S., & Kim, D. K. (2006). The effect of speech rate on the sentence perception of cochlear-implanted, hearing-impaired people. *Journal of Speech Sciences (Korea), 13(2),* 47-58

Oral and poster presentation

Shin, S. & Katz, W. (2017, November). *Cognitive factors involved in the speaking rate difficulties in children with cochlear implants.* Poster session presented at the Annual Convention of American Speech-Language-Hearing Association (ASHA), Los Angeles, CA.

Shin, S., Katz, W., & Warner-Czyz, A. (2016, April). *Speaking rate development of cochlear implanted users.* Poster session presented at the Callier Promotion of Academic and Clinical Excellence (PACE) forum, Dallas, TX.

Shin, S., & Tobey, E. (2013, June). *Speech intelligibility from early speech production in cochlear implantation.* Symposium conducted at International Federation of Oto-Rhino-Laryngological Societies (IFOS) conference, Seoul, Korea.

Peskova, O., Srinivasan, N. K., **Shin, S.**, Sundarrajan, M., & Tobey, E. (2013, June). *Influence of cochlear implantation on sentence intelligibility and duration.* In Proceedings of Meetings on Acoustics ICA2013 (Vol. 19, No. 1, p. 060131). ASA.

Shin, S., & Tobey, E. (2012, November). *Speech intelligibility development of cochlear implanted children.* Poster session presented at the Annual Convention of ASHA, Atlanta, GA.

Tobey, E., Prashant, M., & **Sujin S.** (2012, June). *Speech acquisition from 3 to 10 years in early-implanted children.* Symposium conducted at International Conference on Cochlear Implants and Other Implantable Auditory. Washington, DC.

Shin, S., & Tobey, E. (2011, November). *Speech intelligibility in cochlear-implanted children: Prediction from early speech production.* Poster session presented at the Annual Convention of ASHA, San Diego, CA.

Peskova, O., Warner-Czyz, A., Tobey, E., & **Shin, S.** (2011, November). *Association between QoL & speech perception skills in CI children.* Poster session presented at the Annual Convention of ASHA, San Diego, CA.

Shin, S., & Tobey, E. (2010, November). *Speech intelligibility in multi-talker babble of cochlear implanted users.* Poster session presented at the Annual Convention of ASHA, Philadelphia, PA

Shin, S., & Tobey, E. (2010, April). *Speech intelligibility of cochlear implanted teenagers in noise.* Poster session presented at the Callier PACE forum, Dallas, TX.

Carla, C., Smith, M., **Shin, S.**, Sundarrajan, M., & Tobey, E. (2009, November). *Speech intelligibility of adolescent cochlear implant users.* Poster session presented at the Annual Convention of ASHA, New Orleans, LA.

Shin, S., Sundarrajan, M., Warner-Czyz, A.& Tobey, E. (2009, May). *Speech intelligibility of cochlear implanted adolescents in noise.* Poster session presented at the 12th Symposium on Cochlear Implants in Children. Seattle, WA.

Shin, S., & Tobey, E. (2009, April). *Speech intelligibility of cochlear implanted teenagers in noise.* Poster session presented at the Callier PACE forum, Dallas, TX.

Sundarrajan, M., **Shin, S.**, & Tobey, E. (2009, April). *Speech intelligibility in children with cochlear implants: outcomes in quiet and noise.* Poster session presented at the American Academy of Audiology, Dallas, TX.

Awards and grants

ASHA Student research grant in Audiology (2016)
UTD small PhD research grant (2016)
ACI Alliance student scholarship award (2015)
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