The Effect of Age of Cochlear Implantation on Speech Intelligibility to Others

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Cochlear implantation is a common surgical procedure for children with profound hearing loss who receive minimal or no benefit from traditional hearing aids. Cochlear implants bypass the damaged portion of the inner ear by providing direct electrical stimulation to the auditory nerve. This electrical stimulation attempts to simulate hearing and is highly successful in many children. However, previous research suggests that most children will need to be implanted at an early age to allow for normal auditory processing of speech signals; normal auditory processing of signals is vital in producing intelligible speech. The goal of the present systematic review is to examine the effect of age at implantation on speech intelligibility, which is defined as the comprehensibility of speech to an outside listener. Providing cumulative evidence that age at implantation significantly impacts speech intelligibility will provide further support for early intervention and implantation in children with profound hearing loss.

Introduction

Speech Intelligibility and Hearing Loss

Speech intelligibility refers to the amount by which a speaker's message is recognized by the listener (Chin et al., 2003), and when impaired, negatively impacts communication (Svirsky et al., 2007, Habib et al. 2010; Van Lierde et al., 2005). Normal or near-normal hearing in at least one ear is required to facilitate typical development of oral language and speech production in children. As a result, if spoken language is inaudible to a child due to bilateral hearing loss, it will be difficult or impossible for the child to develop intelligible speech (Khwaileh & Flipsen, 2010). Access to linguistic input is required for an individual to develop the phonological representations that make up the roots of spoken word production (Ambrose et al. 2014). It is important to note that, according to a published study of 74 children as well as a critical review of five peer-reviewed, published studies, even a unilateral hearing loss may negatively affect language development relative to peers with normal hearing (Jośe, Mondelli, Feniman, & Lopes-Herrera, 2014; Lieu, Tye-Murray, Karzon, Piccirillo, 2010)

Optimal hearing is critical for speech and language development as well as speech intelligibility for at least two primary reasons. First, if the speech frequencies are inaudible (i.e., 250-6000 Hz), children will either be unaware of environmental speech or will receive a degraded and inconsistent signal due to the sensorineural hearing loss, which most often occurs in the high-frequency region where most consonants reside. Second, hearing and adequate audibility are necessary to self-monitor speech production.

When considering the impact of hearing on speech and language, typically developing children with normal hearing are 50 to 75% understandable at three years old and 100% understandable at five years old (Peña-Brooks & Hegde, 2015). Conversely, at four to five years old, a child with profound hearing loss and no amplification will have the vocabulary of only a few single words. According to Peng et al. (2004), the average speech intelligibility in profoundly hearing-impaired individuals without cochlear implants is 20%. Without cochlear implantation or traditional amplification that provides adequate audibility, children with profound hearing losses will have speech that is characterized by articulation, voice, speech, prosody and resonance problems as well as developmental delays in form (phonology, syntax, morphology), content (vocabulary and semantics), and use (pragmatics) of language (Northern & Downs, 2002; Schow & Nerbonne, 2013). These children will also exhibit disordered production of consonants and vowels, speech breathing, resonance and the production of suprasegmental features (Schow & Nerbonne, 2013; Van Lierde et al., 2005). Also, as a consequence of absent auditory feedback, many children with severe-to-profound hearing impairments will have deviant nasal resonance and a slow speaking rate (Baudonck et al., 2015). To develop intelligible speech, children must be able to regulate their rate of speech and exhibit concise placement or manner of the articulators. Manner of articulation is defined as the interaction and configuration of the articulators (tongue, lips, and palate) during speech. In addition to speech and language issues, children who do not utilize spoken language may exhibit difficulty with literacy and reading. The ability to express or comprehend written language strongly correlates to comprehension of oral language (Northern & Downs, 2002). Therefore, children who are born with severe-to-profound hearing loss will likely experience greater challenges while learning how to write and read when compared to normal-hearing peers (Svirsky et al., 2007). Some of these difficulties may relate to inadequate development of phonological awareness (rhyming, alliteration, etc.) in children with hearing loss, which is an important precursor to reading ability (Schow & Nerbonne, 2013).

When considering speech intelligibility of children who use hearing technology, a child with a severe-to-profound hearing loss that utilizes hearing aids will have significantly poorer speech production and intelligibility than a child with a cochlear implant (Van Lierde et al., 2005; Sininger et al., 2014). Children with a cochlear implant will have 80 to 90% intelligible speech after 8 to 10 years of implant experience (Tobey et al., 2011). Cochlear implants aid in the production of spoken language in both children and adults with severe-to-profound hearing impairments. When the cochlear implant is in use, hearing thresholds are often in the near normal-to-normal range in the speech frequencies (Wolfe & Schafer, 2015). Speech intelligibility is one effective way to quantify the benefit of cochlear implants on the production of speech because it addresses the communicative properties of language (Chin et al., 2012). The goal of human communication is to make oneself understood and the inability to develop intelligible speech can lead to a communication disability (Khwaileh & Flipsen, 2010).

Although the benefits of cochlear implants are well-documented for children with severe-to-profound hearing loss (Svirsky et al. 2007; Geers et al., 2010; Sininger et al., 2010), there are several criteria a child must meet before being eligible to receive an implant. The United States Food and Drug Administration (FDA) publishes guidelines on who can receive a cochlear implant and at what age implantation can occur (Cochlear Implant Eligibility, n.d.). For example, before a child is implanted, he or she is recommended to use a hearing aid for a trial period of three to six months, experience limited progress with appropriately fit hearing aids, and poor speech perception (Geers et al., 2010). Additionally, the FDA recommends children to be at least 12 months old before receiving a cochlear implant (Habib et al., 2010). Due to these stipulations, the majority of children do not receive cochlear implants until after their first birthday. Normal-hearing, typically-developing children speak their first word at 12 months, while children with hearing impairment usually do not receive an implant to begin language development until 12 months (Cochlear Implant Eligibility, n.d.). Hearing impairments can be identified with newborn hearing tests at birth, but children are not implanted until after 12 months of age unless the implantation is completed off-label. Implantation after 12 months precludes normal speech and language development because hearing is critical to language development and a recipient does not hear until implant activation. Speech and language development begins in infancy, and according to Ambrose et al. (2014), normal-hearing children typically experience rapid development of their speech sound systems just prior to their second birthday. Hence, earlier implantation will provide access to speech sounds required for the development of speech intelligibility. According to Geers et al. (2010), congenitally deaf children implanted at the youngest possible age are more likely to develop age-appropriate language and reading skills than children who receive implants at 4 to 5 years old. Geers et al. (2010) also states that children whose profound hearing loss occurred shortly after birth exhibited higher long-term communication outcomes if they received a cochlear implant shortly after the development of their hearing loss. Therefore, the age of implantation is a crucial predictor of speech development, which continues to develop through early childhood (Schow & Nerbonne, 2013; Chin et al., 2003; Peng et al., 2004; Connor et al., 2014). In addition to the initial gains made in language and speech immediately after cochlear implantation, additional improvements continue for 10 to 15 years post implantation (Beer et al. 2014). According to Tobey et al. (2011), speech intelligibility continues to improve from elementary school through adolescence.

Importance of Speech Intelligibility

Adequate development of speech intelligibility is important for at least four reasons: integration into society, access to mainstream education, quality of life, and psychosocial development. Intelligibility affects societal interactions because the majority of people communicate with oral speech, and, therefore, intelligible speech is required in order to interact with the world (Svirsky et al. 2007). A major factor affecting how well an individual with cochlear implants will integrate into society is related to meeting intelligibility expectations of his or her communication partner, which the communication partner bases on experience speaking with other individuals of similar age with normal hearing (Chin et al., 2003). To make oneself understood by others is imperative to human interaction, and the failure to develop completely intelligible speech may result in difficulties (Flispen & Colvard, 2005). Additionally, it is important that children with hearing loss are able to communicate with children of their own age because peer relationships are models for self-identity and proper behavior (Northern & Downs, 2002; Theunissen et al., 2014).

Second, speech intelligibility is important for full integration into mainstream classrooms, a goal of many parents of children with hearing loss and cochlear implants (Schow & Nerbonne, 2013). Improved technology, refined rehabilitation, and the ability to implant at an earlier age have resulted in pressure to place children with cochlear implants into mainstream educational settings (Chin et al., 2003). Although some children who use manual communication systems (e.g., American Sign Language) can be successful in general education or mainstreamed classrooms, most of these classrooms require high levels of oral-aural communication and depend on speech and auditory skills (Habib et al., 2010). Mainstreaming aims to provide the hearing-impaired child with the least restrictive educational environment, which provides the best access to academic, emotional, and social support (Schow & Nerbonne, 2013). In addition, mainstream, general-education classrooms will allow children with cochlear implants to interact with normal-hearing peers of the same age, which will foster the adequate development of social skills. Cochlear implantation by the age of three can promote spoken language and integration into a mainstream academic classroom (Ertmer, 2007). However, children with profound, unaided hearing losses may only acquire speech and language through rigorous special education classes or through the use a qualified sign language interpreter, which may not be available in a child's home school.

The third reason that speech intelligibility is important is that it will likely affect the child's quality of life for families that choose spoken language as the child's primary mode of communication (Langereis & Vermeulen, 2015). Based on previous research, both speech and severe hearing impairments negatively impact the health-related quality of life of parents of children with these disabilities as compared to parents of children with typical functioning (Aras et al., 2014). However, according to a study including 161 parents, a higher quality of life is found for children with hearing loss after cochlear implantation (Yorgun et al., 2015). More specifically, the majority of parents reported that articulation improved after implantation (77%), children could converse without visual cues (80%), and self-confidence and independence increased (both 85%). In social situations, parents reported that 90% of children were more talkative and conversational, 86% were more sociable in family gatherings, and 88% made friends more easily.

Many children, who receive cochlear implants at an early age and enter Kindergarten at five-years old, will be able to understand others without lip reading, sign language or other visual cues (Schow & Nerbonne, 2013; Yorgun et al., 2015). The ability to hear and acquire speech and language allows a child to develop the ability to think independently, develop self-control and self-direction, and maintain healthy relationships with others. As reported in the aforementioned quality-of-life research (Yorgun et al., 2015), cochlear implantation gives a school-age child with profound hearing loss the ability to socialize with other individuals more frequently. This allows the child to develop appropriate interpersonal skills needed to transition into functional settings, such as employment and post-secondary education (Schow & Nerbonne, 2013). Additionally, children with hearing impairments are usually born into normal-hearing families who want the children to participate in the family community (Tobey et al., 2011).

Finally, the adequate development of psychosocial skills is affected by a child's speech intelligibility, particularly for children with hearing loss who are educated in general education classrooms. Adequate self-esteem is necessary for the development of healthy psychosocial skills, allowing children to adjust to stress and burdens (Theunissen et al., 2014). Self-esteem is one's general appraisal of the self, including feelings of self-worth. The way an individual feels about his or her self affects friendships, academic careers and successes. It is important to have a sufficient level of self-esteem because individuals with higher levels of self-esteem are better adjusted to handle stressful life events, while those with lower levels of self-esteem feel greater amounts of loneliness, peer rejection and psychopathology. Individuals with hearing impairments encounter difficulties regarding self-esteem because they face speech and language delays, problems with communication and less or no access to the sound-dominated world. Cochlear implantation allows a child to develop the language and communication skills required to connect with peers and create solid social networks (Theunissen et al., 2014).

An individual describes, interprets and understands his or her emotions through language. Children with profound hearing loss may have restricted experience with self-expression and a delay in the understanding of their own emotions (Schow & Nerbonne, 2013). They do not have the opportunity to listen to adults and other children verbally manage their feelings about experiences and situations. Children with profound hearing losses are not as accurate in recognizing the emotional states of others compared to their normal hearing. They also have less understanding of emotional vocabulary (Schow & Nerbonne, 2013). According to Chin et al. (2012), prosody is important for the accurate transmission of meaning and is, thus, important for adequate speech intelligibility. Chin et al. (2012) also reports that the control over prosodic aspects, such as intonation and stress, could be problematic because these constructs align with multiple physical parameters (duration, intensity, etc.). In addition, children with profound hearing losses may develop a poor self-concept due to negative reactions to their communication difficulties. They may feel less socially accepted and have lower self-esteem than their normal hearing peers (Theunissen et al., 2014). A delay in language and speech acquisition can negatively affect the development of self-identity (Schow & Nerbonne, 2013; Theunissen et al., 2014).

Rationale for Critical Review

Given the importance of speech intelligibility for societal integration, unrestricted educational success, quality of life, and psychosocial function, an investigation into the demographic characteristics that affect speech intelligibility of children with cochlear implants was conducted. To achieve this goal, a systematic review was performed on peer-reviewed research pertaining to factors influencing speech intelligibility of children with cochlear implants. Systematic reviews and meta-analyses provide the highest level of evidence in the professions of audiology and speech-language pathology because they summarize data from multiple studies over a given time period. These comprehensive reviews also facilitate evidence-based practice and, in some cases, may be used to facilitate changes in insurance coverage for medical devices, such as cochlear implants. The primary hypothesis of this systematic review was that the age at implantation would be the strongest predictor of speech intelligibility, thus providing additional support for the early intervention and implantation of cochlear implants during the critical period of speech, language and auditory development. This hypothesis was derived from research on central auditory development in cochlear implants users showing that stimulation must be presented to a human sensory system within a small window (sensitive period) during development, before 3.5 years, for this sensory system to develop adequately (Sharma et al., 2002). This sensitive period is a time when the central auditory pathways are maximally plastic and ready for development driven by stimulation (Sharma et al., 2009). Furthermore, according to Tobey et al. (2011), diminished or absent auditory input during the formative years may result in poor speech and expressive communication abilities. Therefore, the primary focus of this investigation was the effect of age at implantation on the perceived speech intelligibility of children with cochlear implants.

METHODS

The systematic review was performed using the methods detailed in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; The PRISMA Group, 2009) guidelines, which provides evidence-based step-by-step guidelines for reporting in systematic reviews and meta-analyses. The PRISMA guidelines provided a 32-item checklist for the necessary components of a successful systematic review.

Article searches were conducted in March 2015, and no additional searches were conducted past March 26, 2015. Articles were found through the following databases: PubMed, ProQuest, ASHA, Theime Medical Publishers, and Gale Group Database using the key words: cochlear implants, speech intelligibility, and children. With the exception of review articles, all studies met the following inclusion criteria: (1) children in experimental studies had at least 6 months of cochlear implant experience; (2) peer-reviewed and published in a scholarly journal after the year 2000; (3) the research was performed in English and in a primarily English-speaking country. Implant use for at least 6 months was required in the selection criteria to include children who were implanted at an older age (> 3 years) and to ensure that children would have stable implant programming (Wolfe & Schafer, 2015). All study designs were included in the systematic review. Initially, approximately 20 studies were identified. The abstracts of these 20 studies were reviewed to see if they met the inclusion criteria. As described in the results section, 13 studies met the inclusion criteria for the review.

General Description of Studies

The 13 studies identified for the systematic review were published between 2004 and 2014. Eleven of the studies included experimental designs, while two studies (Dowell et al., 2011 and Flipsen, 2008) were review articles summarizing the effect of cochlear implantation on speech intelligibility. Seven of the eleven experimental studies shown in Table 1 used the Beginner's Intelligibility Test (BIT; Osberger, Robbins, Todd, & Riley, 1994) as the method of determining speech intelligibility. The four remaining studies used various measures listed in Table 1.

Table 1. Description of Experimental Studies

Author/Year	# Of Subjects	Ages of Subjects at Implantation	Test
Beer, 2014	42	8.28 - 47.70 months	BIT, PPVT-3
Chin, 2003	49	17 - 70 months	BIT
Chin, 2012	15	8.27 - 40.44 months	BIT, PUP
Connor, 2006	100	12 - 120 months	PPVT-3, AAPS, GFTA
Ertmer, 2007	6	10 - 36 months	BIT
Flipsen, 2006	6	20 - 36 months	PPVT-3, II-Original, II-AN
Habib, 2010	37	8 - 40 months	BIT
Khwaileh, 2010	17	14 - 100 months	BIT, CSIM
Montag, 2014	63	27.9 - 47.7 months	MSIT
Peng, 2004	24	30.9 - 132.5 months	SLST
Svirsky, 2007	67	20.14 - 83.17 months	BIT, MS

Note. BIT = Beginner's Intelligibility Test, MS = Monson's Sentences, PPVT-3 = Peabody Picture Vocabulary Test 3, PUP = Prosodic Utterance Test, AAPS = Arizona Articulation Proficiency Scale, MSIT = McGarr Sentence Intelligibility Test, GFTA = Goldman-Fristoe Test of Articulation, SLST = Short-Long Sentence Test, CSIM = Children's Speech Intelligibility Measure, II-Original = Intelligibility Index Original, II-AN = Intelligibility Index Age-Normalized

Most of the studies in Table 1 utilized a cross-sectional group design; however, five studies involved single-subject designs (Ertmer, 2007; Flipsen & Colvard, 2006; Khwaileh & Flipsen, 2010; Peng et al., 2004; Svirsky et al. 2007). Two studies used longitudinal designs (Ertmer, 2007; Connor et al., 2006). More specifically, Ertmer (2007) conducted a longitudinal study and used the BIT to assess the same group of six participants at 24, 30 and 36 months after the participants received cochlear implants. Similarly, Connor et al. (2006) used a longitudinal study to test participants on several measures after they had 12 months, 24 months and 36 months of implant experience.

As shown in Table 1, the number of subjects in each study ranged from 6 to 100. All of the experimental studies, excluding Flipsen & Colvard (2006) and Peng et al. (2004), used three unfamiliar normal hearing listeners to judge the speech intelligibility of the participants. The unfamiliar listeners used by nine of the eleven experimental studies were chosen by set of study-specific criteria. According to the guidelines set by the BIT, the criteria for a listener judge is: (1) age between 18-40 years, (2) normal speech and hearing, (3) English as native language, (4) minimal or no experience with the speech of an individual with a hearing impairment. The implanted child eliciting the sentences during the BIT is recorded and played for each judge twice. The judges record what they believe the child is saying, and a score is given based on the match between the judge's responses and the target sentences (Osberger et al., 1994). The conversational speech samples recorded by Flipsen & Colvard (2006) were transcribed by a trained graduate student clinician who completed a phonetics course as an undergraduate student. The graduate student transcribed several conversational samples of delayed speech that had been previously transcribed by a clinician with over 20 years of experience in phonology. Peng et al. (2004) used a write-down method to judge intelligibility. For the write down method, each judge would listen to the sentence twice, write down the recorded sentence, and, then, rate the sentence on a 5-point rating scale. A rating of one indicated that the sentence was not intelligible at all, and a rating of five indicated that the sentence was completely intelligible. The majority of the studies included participants who were implanted before the age of three, while certain studies, listed in Table 2, included both participants who were implanted before and after the age of three.

Table 2. Summary of Results

Author, Year	Ages	Results	Description
Beer, 2014	Age < 3	PPVT-3 & BIT highly correlated	Preschool speech/language development is predictive of long-term speech intelligibility
Chin, 2003	Age < 3	r = 0.710 correlation BIT & age	Correlation between BIT & chronological age
Chin, 2012	Age < 3	84% SI of declarative sentences	Declarative Sentences are best for determining SI
Connor, 2006	Age < 3, Age > 3	Children implanted before 2.5 yrs (group A1) had high SI %	Earlier age of implantation is more beneficial than longer length of use
Ertmer, 2007	Age < 3	Mean SI scores increased 28-62% during third year of CI use	5/6 made greater progress in the 3rd year of CI use
Flipsen, 2006	Age < 3	SI from II-Original 85.7(7.9) SI from II-AN 87.7(7.1)	Age can be used to measure the SI of children implanted before age 3
Habib, 2010	Age < 3	SI ≥ 50%	Children who receive CI's before 2 have high SI rates by 6
Khwaileh, 2010	Age < 3, Age > 3	< 3 SI 72.11(17.79) > 3 SI 41.88(25)	SI and age of implantation are correlated, but not with chronological age
Montag, 2014	Age < 3	89.7 % had intelligible speech	Individual factors that affect NH children also affect children w/ CI's
Peng, 2004	Age < 3, Age > 3	Recognition = 68% correct, Intelligibility = 71.54%	Implanted at younger age resulted in better speech intelligibility
Svirsky, 2007	Age < 3, Age > 3	SI ≥ 90%	CI implantation before the age of 2 may have better SI than later implantation

Note:
BIT = Beginner's Intelligibility Test, CI = cochlear implant, SI = speech intelligibility

RESULTS

Primary Factors Influencing Performance

Upon examining results across the 11 experimental studies (Tables 1 and 2), performance was significantly influenced by three primary factors: (1) age at implantation, (2) chronological age, and (3) implant experience.

Factor 1: Age at Implantation

First, results of all but one study supported the hypothesis that speech intelligibility levels would be higher with earlier implantation. For example, Connor et al. (2006) investigated the correlation of speech intelligibility with the age at implantation in a study with 100 participants who received implants between the ages of 12 months and 10 years. The participants were divided into four subgroups based on age (group A1 = 1 to 2.5 years, group A2 = 2.6 to 3.5 years, group B = 3.6 to 7 years, and group C = 7.1 to 10 years). The participants were assessed with numerous speech and language measures, listed in Table 1, before and after cochlear implantation. These measures included the Peabody Picture Vocabulary Test 3 (PPVT-3, Dunn & Dunn, 1981), a receptive vocabulary test, and the Goldman-Fristoe Test of Articulation (GFTA, Goldman & Fristoe, 1969) or Arizona Articulation Proficiency Scale (AAPFS, Fudala, 1974), tests of consonant production accuracy (SPEECH). According to the GFTA and AAPFS, group A1 had significantly better consonant production accuracy when compared to the other three groups and was predicted to continue to surpass the other groups as they age.

Similar to the previous study, Svirksy et al. (2007) reported a relationship between *the age of implantation* and intelligibility in children with three to six years of implant experience, who attained intelligibility scores ranging from 78 to 94% when rated with the BIT. In another similar study, Habib et al. (2010) found that children tested past the age of 5.5 years old, who received cochlear implants sometime between 8 to 24 months of age, had an average intelligibility score of 93%, compared to only 80% for the children who were implanted at the age of 35 to 40 months. The researchers in the Habib et al. (2010) study found that all children who were implanted between the ages of 8 to 24 months achieved speech intelligibility ratings of 80% or higher after the age 5.5 years. Children implanted from 25 to 35 months averaged 15 to 18% lower than the group of children that were implanted at 8 to 24 months old. However, there were no differences in speech intelligibility scores of children who were implanted at 8 to 12 months and children implanted at 13 to 24 months. Furthermore, the authors also reported that 3 of their 37 participants, who were implanted before the age of three, had higher speech intelligibility scores than their normal hearing peers. Svirsky et al. (2007) and Habib et al. (2010) used identical methodology when conducting their studies, but Svirsky reported different findings. Two of the three participants that surpassed their normal-hearing peers in the Habib et al. (2010) study were implanted before the age of two. In comparison, 14 of the participants tested by Svirsky et al. were implanted before the age of 24 months, but none surpassed their normal-hearing peers. These two studies highlight the inherent variability associated with performance outcomes in children with cochlear implants.

The importance of speech intelligibility as it relates to overall communicative success is emphasized in Beer et al. (2014), where the authors stated that the speech intelligibility rating (determined by the BIT) in preschool were found to predict long-term speech intelligibility and language capabilities. The investigators reported a correlation between receptive language and speech intelligibility; the preschool BIT administered to the participants accounted for 34 to 39% of the variance in the long-term performance on the Peabody Picture Vocabulary Test-4 (PPVT-4; Dunn and Dunn, 1997, 2007), a receptive vocabulary test, and Clinical Evaluation of Language Fundamentals (CELF-Core; Semel et al., 2003) receptive language scores.

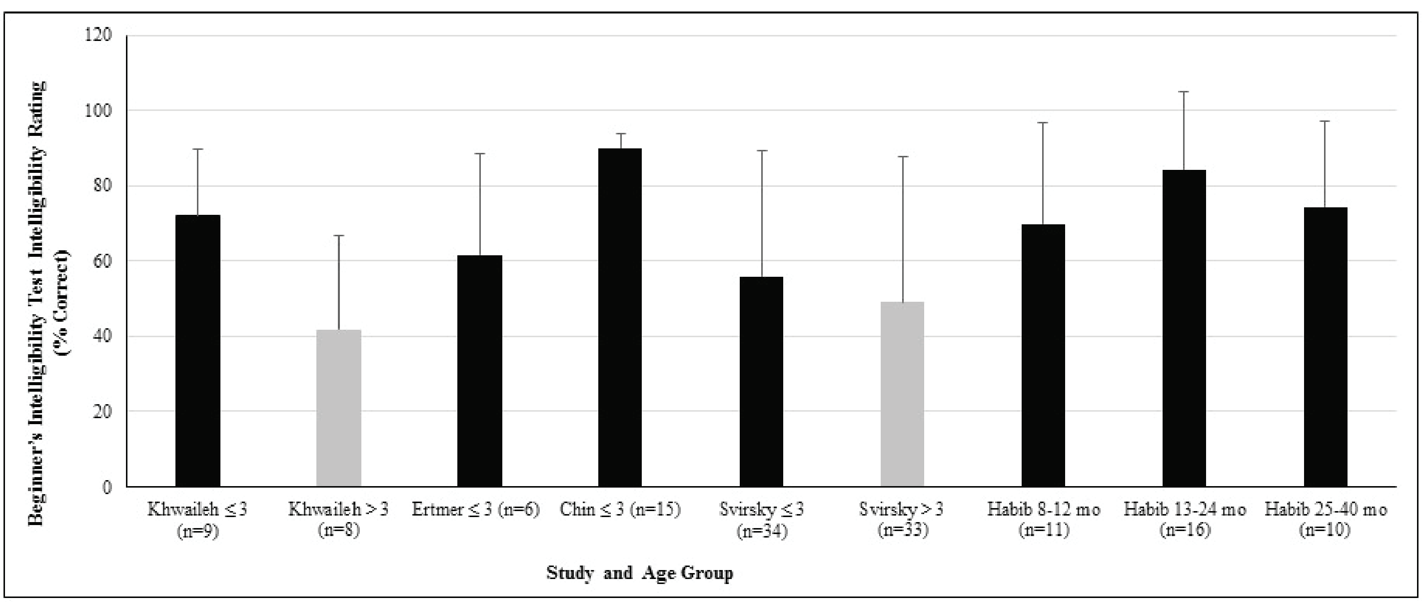

Figure 1. Average speech intelligibility ratings from the experimental studies providing average or raw data. Note. Vertical lines represent one standard deviation; number provided after primarily study author represents the age at cochlea implantation..

When examining results across the studies that investigated the effect of age at implantation on speech intelligibility, the results seen in Figure 1 support the hypothesis that children who are implanted before the age of three have higher intelligibility scores than children who are implanted after three. However, it is important to note the large variability across studies and even within studies. Therefore, it is difficult to make very strong conclusions with the data currently published in the field.

Factor 2: Chronological Age

The second major factor, *chronological age* at the time of testing, is also highly correlated with speech intelligibility ratings. More specifically, Beer et al. (2014), Connor et al. (2006), Chin et al. (2003) and Chin et al. (2012) stated that there was a significant correlation between chronological age at testing and speech intelligibility. For example, Chin et al. (2012) reported a significant correlation between the BIT score and chronological age (r = .71). Similarly, Chin et al. (2003) found a significant correlation between intelligibility scores and chronological age (r = .60). Flipsen & Colvard (2006) found multiple factors to be significantly correlated with speech intelligibility, but chronological age was the strongest factor (r = .64-.66). It is important to note that Flipsen & Colvard (2006) only tested children who received cochlear implants before the age of three. Therefore, Flipsen & Colvard (2006) believe that chronological age should be used to set expectations for levels of speech intelligibility in children who receive cochlear implants before the age of three.

Conversely, Khwaileh & Flipsen (2010) stated that speech intelligibility scores were not significantly correlated with *chronological age* (Pearson correlation r = .28-.42). The investigators administered three intelligibility tests, listed in Table 1, to a group of 17 participants who were all implanted before the age of eight. Results across the test measures showed the highest scores were reported on the Children's Speech Intelligibility Measure, scored by multiple-choice (CSIM-MC; Wilcox and Morris, 1999) test. The CSIM-T, scored by transcription (Wilcox and Morris, 1999) yielded scores that were strongly correlated to scores on the CSIM-MC (r = .85). The third measure, the BIT, resulted in higher scores than the scores than the CSIM-T, but these scores were lower than the scores on the CSIM-MC. The BIT and CSIM-MC scores were correlated (r =.89), and the BIT scores were also correlated with the CSIM-T scores (r = .78).

In the Kwaileh & Flipsen (2010) study, some children that were similar in age had drastically different BIT scores. For example, Participants #1 and #2, who only differed in age by six months at the time of testing, performed differently on the BIT measure. Participant #1 had a score of 12 on the BIT, while Participant #2 had a score of 74. Similarly, Participants #9 and #15, who were both 118 months at the time of testing had varying intelligibility scores. Participant #9 had a score of 85 on the BIT, while Participant #15 had a score of 73, thus supporting the authors' conclusion that chronological age is not correlated with intelligibility.

Factor 3: Implant Experience

In the Khwaileh & Flipsen (2010) study, *implant experience*, the third major factor identified in this systematic review, was the only factor significantly correlated with speech intelligibility (r = .58-.67). More specifically, intelligibility scores at both single and sentence levels were correlated with implant experience. As mentioned in the previous section, chronological age did not appear to correlate strongly with speech intelligibility, possibly because of the narrow range of chronological ages (4 to 11 years). However, the length of implant experience in this study ranges from 12 months to 94 months, allowing for a broader distribution of data points.

Other Factors Influencing Performance

In addition to age at implantation, chronological age, and implant experience, there are additional factors that could affect the speech intelligibility ratings identified in the aforementioned studies. Some of these factors may include the sample size, study design, the time each participant spent in speech therapy, the intelligibility tests proctored, and the individual differences of each participant.

First, it is important to note that the sample size and the study design used in each study could have influenced the intelligibility scores of the participants and the variability associated with the findings. For example, Chin et al. (2003) included 15 participants with cochlear implants and only 10 participants with normal-hearing, resulting in unequal experimental and control groups. Additionally, a smaller sample size results in greater variability. As stated previously, the sample sizes of the studies included in this systematic review ranged from 6 to 100 participants.

The study design used within each study may also impact results. In several studies, a within-subjects group design was used, and as a result, no control group was used to compare the scores of the children with cochlear implants.

Second, the time the participants spent in speech therapy could have affected the scores on the speech intelligibility tests. If a participant spent more time in speech-language therapy, or was introduced to speech-language therapy at an earlier age than the other participants were, their intelligibility ratings could have been skewed positively. A gender effect could have been present in several studies, potentially skewing data. For example, Khwaileh & Flipsen (2010) conducted a study with 17 participants. Four of those participants were male, and 13 were female. This unequal distribution of male and female participants could have resulted in a gender effect. However, these factors were not explicitly addressed in the studies used in this systematic review and cannot be used to explain the variability of intelligibility scores at this time.

Third, the types of intelligibility rating tests proctored and the judges could have affected the results presented by each study. The majority of the studies included used the BIT as the main measure of obtaining speech intelligibility ratings, but other methods, such as the Intelligibility Index and GFTA were also used. As stated previously, the BIT is an objective test to measure the intelligibility of a child's speech. Using the BIT, an audio recording of a child eliciting 10 sentences is played to a panel of unfamiliar listeners. The listeners write what they believe the child has said the percentage of words understood correctly is calculated. The majority of the studies used three normal-hearing, adult listeners as judges of the participants' speech intelligibility levels through a rating system. Other studies used a write-down method to calculate intelligibility ratings. In the write-down method, judges wrote what they heard the participants say, and those results were contrasted with the correct sentences. Peng et al. (2004) used the write-down method with the Short-Long Sentence Test (SLST), which is a component of the procedure used in the Iowa Children's Cochlear Implant Project. In this study, the children were recorded modeling 14 sentences. The recordings were transcribed by 72 adult listeners recruited from the University of Iowa campus. According to Peng et. al (2004), the rating scale is more efficient because it takes less time to calculate a speech intelligibility score, but the write-down method allows for analysis of specific error patterns.

Although not a factor, it is important to consider the individual differences of each child with a cochlear implant, which makes it difficult to clearly examine all factors. Children develop language at different rates and individual differences can account for differences in the time it takes for a child to learn language. For example, Svirsky et al. (2007) reported that in a group of children implanted before the age of two, several participants reached 95% intelligibility after a few years of device use, while other participants did not. As a result, large sample sizes are necessary when examining any factor related to performance.

DISCUSSION

Age at Implantation

The primary purpose of this systematic review was to examine if children who receive cochlear implants before the age of three years will have higher levels of speech intelligibility than children who receive implants after the age of three years. The majority of the studies included in this systematic review supported the idea that earlier implantation results in higher levels of speech intelligibility, thus providing more support to early intervention and implantation. More specifically, the age at implantation proved the most important factor influencing a child's speech intelligibility; five studies concluded that the age of implantation directly influences the speech intelligibility of a child (Flipsen & Colvard, 2006; Connor et al., 2006; Beer et al., 2014; Montag et al., 2014; Ertmer, 2007). The data in Figure 1 clearly illustrate the high levels of speech intelligibility obtained with the implant. However, four studies included limited data on children who were implanted past the age of three years old.

According to Connor et al. (2006), children who received cochlear implants at a younger age demonstrated stronger outcomes at any given age than their same-age peers who received cochlear implants at an older age. These stronger outcomes were related to the amount of implant experience; children who received the implant at a younger age had more implant experience. Connor et al. (2006) observed a length-of-use effect; children who had earlier access to spoken language and sound had higher rates of vocabulary and speech-production accuracy. Similarly, Montag et al. (2014) suggests that implanting children as young as possible optimizes adequate language development. Montag et al. (2014) determined the age at implantation to be a significant factor influencing the overall speech intelligibility of a child. The investigators also stressed the importance of maximizing the quantity of spoken language in which a child is exposed after receiving the implant. A combination of early implantation and a large amount of verbal interaction experience will provide a child with the best outcome for speech intelligibility. Age at implantation and exposure to spoken language were significant predictors of future language capabilities. Additionally, Beer et al. (2014) observed that the age at implantation and the onset of deafness were the only two variables that had a significant impact on the ability to predict preschool speech intelligibility and later speech and language outcomes.

The Existence of a Sensitive Period

While the majority of the studies included in this systematic review supported the implantation of children before three years of age, five studies (Connor et al., 2006; Habib et al., 2010; Flipsen & Colvard, 2006; Svirsky et al., 2007; Ertmer, 2007) also discussed the existence of a sensitive period for cochlear implantation. When children received implants before 2.5 years old, a sensitive period of speech and language growth was observed.

First, Connor et al. (2006) observed significant growth immediately after implantation in children who received the implant before the age of 30 months. Children who were implanted at 1 to 2.5 years of age demonstrated an early surge of consonant-production accuracy that continued for about two years before slowing to rate similar to the children who were implanted at 2.6 to 3.5 years of age or 3.6 to 7 years of age. Children who were implanted before 2.5 years of age had faster rates of vocabulary and consonant production accuracy than the other groups included in this study.

Second, Habib et al. (2010) stressed implanting children with cochlear implants before their second birthday. This study was significant because the investigators explored the differences between children who were implanted between 8 and 24 months of age and children implanted at 25 to 35 months of age. While the purpose of this systematic review was to compare speech intelligibility in children implanted before and after three years of age, this article provided insight into the potential benefit of implanting children earlier than 12 months of age, which is the earliest age recommended for implantation by the FDA. As stated in the results section, the groups of children implanted at 8 to 12 months and 13 to 24 months had slightly higher speech intelligibility ratings when compared to the children implanted after 24 months. However, when comparing the children who were implanted at 8 to 23 months to those who were implanted at 13 to 24 months, there were no evident differences in speech intelligibility between the two groups. The data found by Habib et al. (2010) does not support a large difference in speech intelligibility between the two earlier-implanted groups. Further research will need to be conducted to provide stronger support for earlier implantation.

Third, Flipsen & Colvard (2006) also support the existence of a sensitive period. The researchers state that intelligible speech emerges quickly in children who are implanted before the age of three years old. All six children included in the Flipsen & Colvard (2006) study were implanted before the age of 36 months; the earliest a child was implanted was at 20 months, and the latest at 36 months. For a child who is implanted by 3 years old, intelligible speech emerges rapidly in the first two years of implant experience.

Neurological Plasticity

In addition, the existence of a sensitive period suggests the existence of plasticity in the neurological systems of young children. According to Connor et al. (2006), the sensitive period suggests a high level of plasticity in the neurological systems fostering vocabulary development, especially those systems associated with the auditory pathways. Connor et al. (2006) also suggests that the window for speech-production accuracy seems to be even wider than the window for vocabulary production. At birth, the typically developing human cochlea is mature, but auditory neural development continues in the brainstem in very early childhood and in the cerebral cortex until late childhood. Adequate development of the auditory system is dependent on stimulation from a diverse auditory environment of relevant sounds (Sininger et al., 2014). According to Sharma et al. (2002), the auditory system is maximally plastic around 3.5 years of age, and cochlear implantation by this age produces the best results in regards to the adequate development of the auditory system. Auditory deprivation for more than seven years considerably alters the development of the auditory system (Sharma et al, 2002). The results obtained by Connor et al. (2006) and Sininger et al. (2014) align with the research on neuroplasticity conducted by Sharma et al. (2002) and Sharma et al. (2009), mentioned previously in the introduction.

Therefore, it is important for a child with severe-to-profound hearing loss to receive cochlear implants before the age of three years old, at the latest, in order to take advantage of the plasticity of the auditory and speech-production systems. Development of intelligible spoken communication is dependent on the ability of the auditory channel to receive and transmit information to the central nervous system during the early stages of development (Sininger et al., 2010). In addition, given the importance of the age at implantation, the FDA age criterion may need to be reevaluated to consider implantation before 12 months of age.

Peak of Speech Intelligibility Development

Additionally, several studies (Chin et al. 2003; Connor et al., 2006; Peng et al., 2014) discussed the existence of a plateau in speech intelligibility development in children with cochlear implants. Chin et al. (2003) stated that children with cochlear implants do not reach a plateau for speech intelligibility, unlike other children with normal hearing, who reach their peak levels of speech intelligibility at four years old. In the Chin et al. (2003) study, children with cochlear implants did not experience plateaus in their intelligibility scores, indicating that children with cochlear implants may continue to increase their speech intelligibility accuracy with age. Similarly, Peng et al. (2014) recorded a continuation in the development of accurate speech intelligibility even after a child has 5-6 years of cochlear implant experience. In the Connor et al. (2006) study, data expressed a lasting rate of speech intelligibility development after implantation for children who received cochlear implants before the age of seven years. It is likely that a plateau does occur at some age or duration of implant use; however, it was not captured in the studies included in this review.

Limitations

Originally, the articles included in this systematic review were to be a part of a meta-analysis. However, numerous studies did not include mean intelligibility scores or standard deviations, which are required for a meta-analysis. This systematic review included a limited number of studies, and only four studies included data on children implanted past the age of three. Additionally, numerous studies used only a few subjects in their experimental design, which could limit the results of this systematic review. It is also important to note that only one study provided CI aided thresholds (Ertmer, 2007). Audibility across the frequency range, and particularly in the speech frequencies, is important for speech intelligibility because it would experience with speech sounds and the ability to monitor (i.e., auditory feedback) his or her own voice while speaking. It would be helpful for future research to see how aided thresholds correlate to speech intelligibility. Furthermore, many of the studies did not specifically state whether children were using unilateral, bilateral, or bimodal arrangements (cochlear implant + hearing aid). There is certainly the possibility that children with binaural hearing (i.e., bilateral or bimodal) could have better speech intelligibility; however, future research will need to test this hypothesis.

Conclusions

The majority of these studies support the hypothesis that a child will have greater speech intelligibility the earlier they are implanted. In addition, several studies indicated implant experience and chronological age contribute positively to speech intelligibility.

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