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Effects of Noise on Speech Perception in Children Using Cochlear Implants: A Systematic Review

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Honors Thesis

University of Connecticut

Abstract

Deaf children often use cochlear implants in settings where background noise is present. This study was designed to review the literature on speech perception in noise abilities of children with cochlear implants. A systematic search of the database Academic Search Premier was used to identify papers. A total of 13 articles were included in this review from an original 144. Results were found to be consistent with other studies. From this review, multiple factors were found to improve speech perception in noise, including using bilateral implants and increased experience with the implants. However, more studies are needed to determine if children are comprehending the information they hear. Additionally, this review makes suggestions for information to be included in future study reports, especially participant age at implantation and language experience.

Effects of Noise on Speech Perception in Children Using Cochlear Implants: A Systematic Review

Cochlear implants are often a common intervention for children born with sensorineural hearing loss. Despite many improvements, these implants are not always successful in providing hearing levels similar to that of typically hearing children, especially in situations with great amounts of background noise. Many studies examine speech perception using cochlear implants, but only a small number test perception in noise. This review paper aims to investigate the effects of noise on speech perception for children using cochlear implants.

Hearing loss

Profound congenital sensorineural hearing loss occurs in 1.1 of every 1000 babies born in western countries (Chen & Oghalai, 2016). In America, over 28 million people experience hearing loss, and around 2 million of these people are considered profoundly deaf (Nadol, 1994). In people who are deaf from childhood, the main concern is access to language. Without access to language, cognitive functions and literacy are often impaired, often leading to worse educational outcomes and fewer employment opportunities (O'Donoghue, 2013).

Sensorineural hearing loss is often associated with damage to the inner ear (Nadol, 1994). In a healthy ear, sound enters through the outer ear. The middle ear then amplifies this sound. Finally, the inner ear converts these sound waves to electrical impulses (O'Donoghue, 2013). The inner ear contains thousands of hair cells and neurons. These neurons synapse on the cochlear nucleus to transmit the electrical impulses to the brain (Nadol, 1994). When these cells are damaged, sound waves cannot be converted to electrical signals, and sensorineural hearing loss occurs (O'Donoghue, 2013).

The level of hearing loss is typically measured by the threshold needed for someone to perceive a sound in decibels (dB). For a typically hearing person, this is usually 0 dB. At a hearing threshold of 25 to 30 dB, a child will likely have difficulty acquiring speech (Nadol, 1994). Profound hearing loss ranges from a hearing threshold of 90 dB to 120 dB, with 120 dB representing complete deafness (Nikolopoulos & Vlastarakos, 2010).

Approximately half of the cases of congenital sensorineural hearing loss are caused by genetic mutations, often a mutation in the gap junction beta 2 gene (Nikolopoulos & Vlastarakos, 2010). Other, non-genetic causes of congenital sensorineural hearing loss include meningitis, congenital cytomegalovirus infection, and exposure to intrauterine infections such as herpes simplex, rubella, and syphilis.

Early identification and intervention

To best identify and treat congenital hearing loss, universal newborn screening is recommended by the age of 1 month (Chen & Oghalai, 2016). Infants who do not pass this screening can be further tested using a combination of three audiological tests: Otoacoustic emissions, auditory brainstem responses, and auditory steady-state responses. (Nikolopoulos & Vlastarakos, 2010) During an otoacoustic emissions test, a small probe is placed in the infant's ears. Sounds are played into the infant's ear, and the sound waves produced in the inner ear are measured. In both auditory brainstem response tests and auditory steady-state response tests, sounds are played to the baby using headphones. Electrodes are placed on the infant's head to measure the auditory nerve and brain response to sound (American Academy, 2018). These additional tests should be completed as soon as possible, and ideally, the infant's hearing status will be confirmed by the age of 3 months (Joint Committee, 2013).

Once the infant's hearing status is confirmed, the family should be entered into an early intervention program. This program should include education about the infant's hearing status, access to other families with deaf children, and access to professionals who can teach the child and their parents American Sign Language (ASL) and medical professionals. For families who choose to have their child learn ASL, the main goal will be teaching ASL to both the infant and the family if needed. For families whose goal is for the child to learn spoken language, the main goal will be to provide access to spoken language as early as possible. It is also important to note that families can choose to do a combination of both. Regardless of the interventions chosen, families should be connected with deaf mentors and other families with deaf infants. Additionally, all deaf children should have their progress monitored from around 6 months of age up to three years. This monitoring should include checking their progress in developing spoken and/or sign language as well as social-emotional, cognitive, and motor skills.

Models of deafness

There are two common models through which deafness is typically viewed. The medical model views deafness as an individual's problem. Through this view, being deaf is a medical condition that should be treated whenever possible (Goering, 2002). The social model, by contrast, claims that deafness is not the individual's fault. Rather, it suggests that deafness, like other disabilities, is challenging only when accompanied by a lack of societal accommodations (Goering, 2002). Supporters of the medical model tend to emphasize the need for cochlear implants while supporters of the social model tend to emphasize the importance of other options, such as sign language interpreters and closed captioning.

Treatment options

For families who want their child to learn sign language, a qualified ASL instructor should be provided for the family. This instructor must be able to provide information about ASL and teach ASL to the parents. This can be done instead of or in addition to learning spoken language.

For families who want their child to learn spoken language, hearing aids are often the first treatment option for deaf infants. Hearing aids are small devices that are placed in the person's ear. These devices amplify sounds so the person can better hear (U.S. Department, n.d.). Hearing aids can be very useful for people with sensorineural hearing loss, but they do have limits. For any infant who is identified as being profoundly deaf, hearing aids should ideally be fitted by the time they turn 3 months old. Their language development should then be closely monitored, and if they are not progressing in the next few months, cochlear implantation should be considered (Nikolopoulos & Vlastarakos, 2010).

Cochlear implants are devices that are surgically implanted into the patient's ear. Instead of amplifying sounds, they instead stimulate the auditory nerve. This concept was first tried in 1957 when a surgeon directly stimulated the auditory nerve of a deaf patient and the person was able to hear some sound. After this, Dr. William House created a device that could stimulate the auditory nerve through the cochlea (O'Donoghue, 2013). In the 1980s, multichannel devices that stimulated the cochlea at multiple points were created (O'Donoghue, 2013).

Currently, cochlear implants include a microphone that detects sounds in the environment. The microphone sends the signals to the speech processor, which converts sounds into electronic signals and sends them to a transmitter coil. This coil then sends signals to a multi-channel receiver, which will stimulate the implanted electrodes and cochlear nerve fibers. Finally, the nerve fibers send signals to the brain, where it is processed (Nikolopoulos & Vlastarakos, 2010). With modern devices, residual hearing in the patient's ear can often be preserved, allowing for better hearing outcomes (O'Donoghue, 2013).

However, despite these improvements, cochlear implants are not perfect solutions, and they can have varying degrees of success. Even when successful, cochlear implants do not restore normal hearing (O'Donoghue, 2013). There are many factors that influence the success of cochlear implants in improving speech perception and production in children. The most significant of these is the child's age at the time of implantation. Increased age at implantation has been shown to be associated with adverse outcomes (Black et al., 2011). Typically, children can be identified as deaf by the age of 1 year old (Shakrawl et al., 2020). For these children, receiving an implant by the age of 3 years at the latest is crucial. By identifying deafness and placing a cochlear implant early, the amount of time the child has no access to sound is decreased. This, especially in families who are not using a sign language, can prevent the infant from falling behind in terms of language development. In addition, implanting these infants prior to the end of their critical period for language development can allow them to learn spoken language more quickly. Children who are implanted at younger ages have been found to develop language faster following implantation than children who are implanted later in childhood (Shakrawl et al., 2020). Oral communication in these individuals is facilitated by speech therapy, implying that early speech therapy should improve language outcomes after implantation.

The family's communication choice, such as using a sign or spoken language, can also influence the success of cochlear implants. In some studies, children who used oral communication exclusively tended to perform better on speech perception and production tests than children who used manual or total communication alongside spoken language (Black et al., 2011). However, part of this difference may be due to the fact that children who use both a sign and a spoken language are bilingual, and their language development should therefore be compared to bilingual children rather than monolingual ones. Age of implantation has been found to have a larger impact than communication mode. Children who are implanted at younger ages who had never used speech therapy had better language outcomes than those who used speech therapy but were implanted later (Shakrawl et al., 2020).

Cochlear implant studies

As of 2016, there are 38,000 cochlear implants in use in the United States (NIH). As a result, there have been many studies aimed at determining factors that influence their success.

There are many different aspects of hearing and auditory processing individual studies may test to determine outcomes after cochlear implantation. Some common examples of these aspects include speech perception, auditory discrimination, spoken language use, and behavioral outcomes. Auditory discrimination tests focus on the participant's hearing level by asking them to differentiate between similar sounds. Spoken language use and behavioral studies focus on other characteristics of the participant's life, such as their ability to communicate with hearing people and emotional factors.

Speech perception tests generally require a participant to listen to a stimulus and then correctly identify it. There are multiple types of stimuli that can be given to the participant. They can contain any level of linguistic complexity and are typically phonemes, monosyllabic words, disyllabic words, or full sentences. Studies also vary in the method that participants identify the target stimulus. Questions can be forced choice, where the participant must select the correct answer from a few options, or open-ended, where the participant must generate the correct response unprompted.

Additionally, speech perception can be tested in either quiet or noisy situations. Historically, many studies that are designed to test the impact of cochlear implants on improving speech perception did so in silent laboratory conditions. While this data is useful in showing that cochlear implantation surgery is successful, they do not translate to real-life scenarios. As a result, speech perception is now often tested in situations with background noise. In these studies, the signal-to-noise ratio (SNR) is used to quantify how much background noise is present. This measure is the ratio of the sound level of the stimulus to the sound level of the background noise, so any SNR above one means the background noise is louder than the stimulus.

The current study

In this review, speech perception was chosen as the metric to evaluate cochlear implants due to its applicability to real-life scenarios. Similarly, the search term "noise" was added to limit to studies that tested the speech perception of the participants in settings with background noise, which are most similar to situations they may encounter in everyday life. Many settings, such as schools, require people to discriminate between which sounds are important and which are background noise. Finally, the search term “children” was added to limit to studies whose participants were 18 years old or younger. Children are often in settings, such as schools, where they are expected to listen to a specific person while there is background noise present. Thus, understanding the extent to which cochlear implants improve their speech perception is crucial.

Many new developments in the design and technologies of cochlear implants have emerged in the past ten years. Implants have become softer and more flexible, and now have lower stimulation thresholds (Eshraghi et al., 2012). These developments have increased the effectiveness of cochlear implants and improved the outcomes of implantation surgeries.

Age of implantation is a major factor affecting the success of cochlear implantation in being able to improve the language abilities of the patient. One study compared language outcomes in two groups of children, one with children who were implanted before the age of 4 and one with children who were implanted after the age of 4. The mean age of implantation in the group implanted before age 4 was 3.25 years. This group was found to have higher scores in both understanding and speaking language when compared to the other group (Shakrawl et al., 2020). While some recent studies show that implantation by the age of 2 is most effective, implantations at age 3 are typically considered to be effective.

Methods

Search terms

This study is a review of papers found using the Academic Search Premier database. Along with “cochlear implant,” the following search terms were used: (“speech perception” OR “speech recognition”) AND “noise” AND “children.”

Selection criteria

Due to the many improvements made in cochlear implant technologies and protocols in recent years, only papers published between 2011 and 2021 were included. Additionally, age at implantation has been shown to have a significant effect on outcomes. As a result, only studies where the participants were under the age of 4 at the time of their first implantation were included. If age at implantation or performance on a speech perception in noise task were not included, the paper was excluded from this study. If other information was missing, it is noted in Table 1**.** Once the search was complete, papers were excluded by the process described below.

Selection process

The titles of each paper were first reviewed to eliminate any duplicates and systematic reviews. After those papers were excluded, abstracts were reviewed to eliminate papers that were irrelevant to the study question. Papers deemed to be irrelevant to the question of speech perception in children were excluded. These studies either did not test speech perception in noise or involved adult participants rather than children. Finally, the full papers were reviewed. Here, studies were excluded for either not reporting the age at implantation or having one that was too high.

Data items

For the papers that met all of the criteria, data items were extracted. Some data items were included to evaluate the study design. These included the specific research question, study size, stimulus presented, and signal-to-noise ratio used. Other date items were included to provide information about the cochlear implant use of the children. These included age at implantation, age at the time of the study, time using the cochlear implant, brand of cochlear implant, hearing aid use, and whether participants had one cochlear implant or two.

Results

Search terms

After searching for the terms listed above, 144 papers were found. From a review of the titles, 4 papers were excluded for being review papers and 6 papers were excluded for being duplicates. Abstract reviews were performed for the 134 papers left, and 55 of these papers were excluded for being irrelevant to the study question. Irrelevant studies typically either involved adult participants or tested speech perception in quiet conditions.

Excluded papers

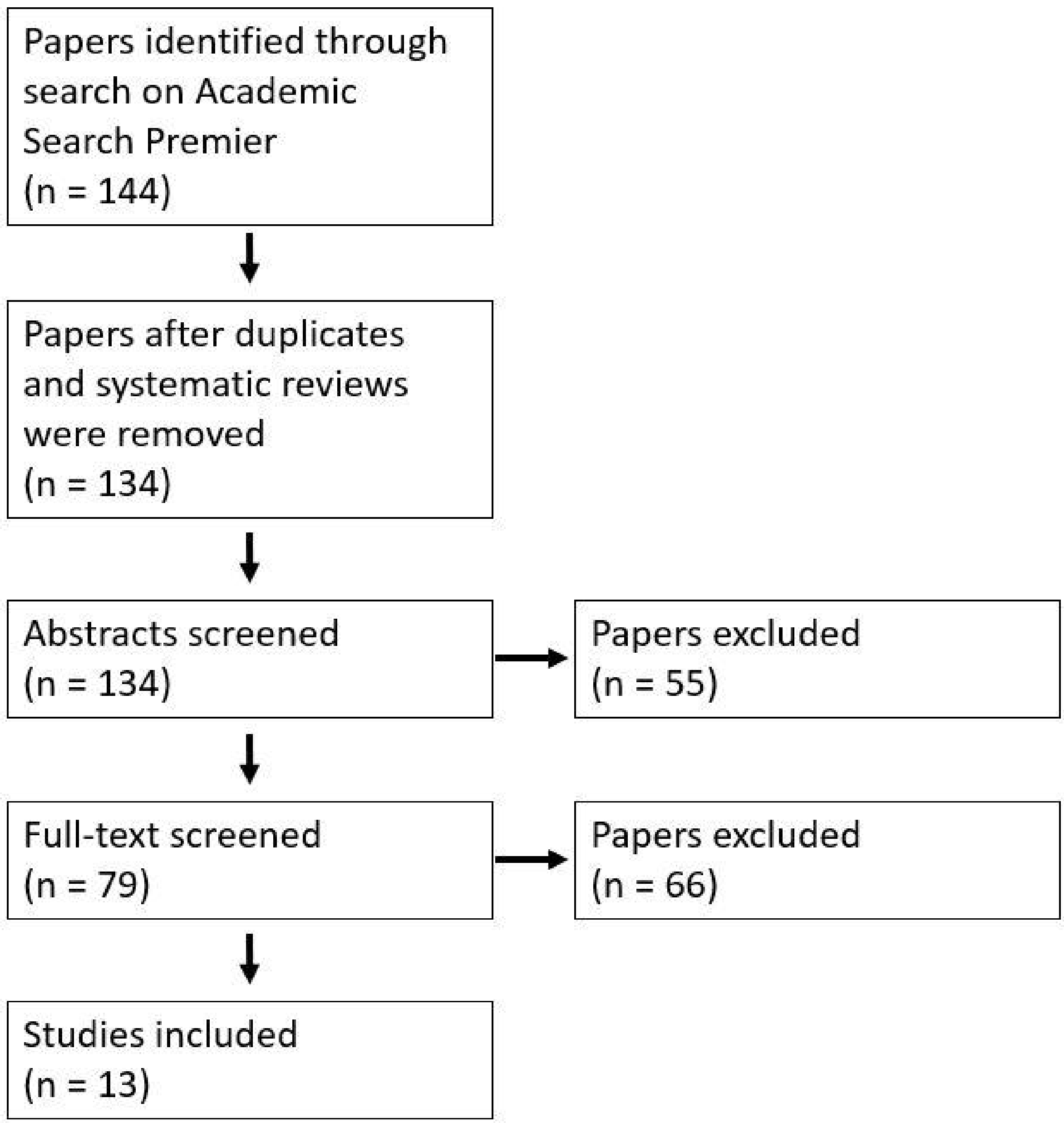
Finally, the full papers were reviewed. The main characteristics searched for are the participants' ages at the time of their first cochlear implantation since this criterion has been shown to have a large impact on the child's language abilities (Chen & Oghalai, 2016). After this review, 66 papers were excluded for either including participants who were implanted at age 4 or older (57), or for not reporting the age of implantation (American Academy, 2018).

Included papers

After this process was complete, there were 13 papers remaining that met all of the predefined criteria.

Figure 1.

Flow chart showing selection process for papers



Study characteristics

A summary of study characteristics can be seen in Table 1. A full description of each study can be found in the appendix. The studies included in this review were all published between 2010 and 2020. Sample size ranged from 10 to 115, with an average of 51 participants.

The stimuli presented to participants varied across papers. Some studies presented words, including monosyllabic words, disyllabic words, and spondees. Other studies used sentences, which were always syntactically correct, but sometimes had no meaning.

Studies also varied in the way noise was added to the experiment. Some studies provided a constant level of noise throughout the experiment. These studies either reported the signal-to-noise ratio or the sound pressure level (SPL) used. In the studies that reported SNR, it ranged from -3 dB to 12 dB. In the ones that reported SPL, it was either 60 dB or 65 dB, which is considered to be approximately the level of daily noise exposure (Lo et al., 2020). Other studies did not provide a constant level of noise. Instead, these studies varied the SNR to find the speech recognition threshold (SRT), or the level at which a participant can correctly identify speech in a set number of trials. One study set this number of trials at fifty percent and found the threshold to be 10.25 dB (Neuman et al., 2011). Other studies set the number of trials to 70 or 71 percent and found the SRT to be between 40 dB and 60 dB.

Participant age at implantation was reported in multiple different ways. Four studies provided only the mean participant age at implantation rather than data on each individual participant. These mean values were between 16 and 22 months. Seven studies reported the maximum age at implantation for inclusion in their study, either with or without other information about age. Four of these studies required participants to have been implanted by age 3, one used at 2.5 years as the maximum, one used age 3.5 years, and one used age 4.5 years. Finally, two studies provided either the range of participant ages or the age of each individual participant. The range of participant ages in these two studies were 0.8 to 2.7 years and 1 year, 2 months to 3 years, 9 months.

Participant age at the time of the study was also reported in different ways. Six studies provided a range of participant ages. In these studies, participant age was between 3 and 12 years. Six studies provided the mean participant age at testing. These mean values were between 5 and 10 years. Finally, one study did not report the age of the participants at the time of the study.

Many studies did not report the amount of time the participants had been using their implants. For the ones that did, there was a range of 2 to 10 years with using the first implant. Many papers did not report the brand or model of cochlear implants being used. For the ones that did, brands included Neurelec, Cochlear, Advanced Bionics, and Med-El, with the most common model being Cochlear's Nucleus 24. Some of the included papers required that participants had used hearing aids prior to implantation, while others did not report this information.

Finally, whether participants had unilateral or bilateral implants was recorded. Out of the fifteen included studies, two studies tested only unilaterally implanted participants, three studies tested only bilaterally implanted participants, and ten included participants with either one or two implants. For the bilaterally implanted participants, whether the implantations were simultaneous or sequential was recorded. For the studies that reported this information, five papers had sequentially implanted patients, one study had simultaneously implanted patients, and three studies had a mix of both.

Table 1.

Summary of study characteristics

Article Number	*Author (Year)*	*Participant Demographics*	*Measure*	*Overall Result*
1	Sparreboom, M. (2010)	N = 38 Age at implantation: x=1.8 yrs, SD=0.5, R=1.1-2.7 yrs in BiCI group. x= 1.6 yrs, R=0.8-2.0 yrs in UCI group	Monosyllabic words	BiCI significantly better for perception and lateralization than UCI. BiCI experience increases BiCI advantage.
2	Neuman, A. (2012)	N = 25 Age at implantation: R=1.0-3.1 yrs (All by 3 years)	Sentences	Worse in noise than quiet. Worse than typically hearing kids in both conditions. SNR50 for individual children between 6 dB and 14.5 dB.
3	Litovsky, R. (2012)	N = 10 Age at implantation: R=1.6-3.8 yrs	Spondee words	BiCI significantly improved at 3 and 12 months. Greater improvement when background noise is in front or near CI1.
4	Caldwell, A. (2012)	N = 54 Age at implantation: x=21 mos, SD=13 mos	Words and phonemes	Words: From ANOVA, SNR $p < 0.001$, Group $p < 0.001$. Speech recognition was worse in poorer SNRs. Children with hearing loss were worse than NH. Age of CI1 implantation significant for phoneme recognition but not word
5	Nittrouer, S. (2013)	N = 113 Age at implantation: x=21 mos, SD=17 mos	CVC words	In quiet, NH kids are better. In noise, kids with CIs were worse than NH or HA - $F(2,110.01) = 172.28$ $p<0.001$. Vocabulary knowledge/sensitivity to phonological structure did not help speech recognition in noise, final consonant choice test was predictor in same condition.
6	Ching, T. (2014)	N = 70 Age at implantation: (All using CI by age 3)	Sentences and words	BiCI and CI+HA needed better SNR than NH but similar to each other. Earlier implantation age was associated with better performance. SNR lower when spatially separated than when together. Children with CI+HA or BiCI required 9 dB better

				SNR for same speech perception as NH.
7	Sparreboom, M. (2015)	N = 50 Age at implantation: x=1.8 yrs in BiCI group, x=1.9 yrs in UCI group (All before 3 years)	CVC words	BiCI did better than UCI (p<0.01). Children in mainstream schools did better than those in deaf schools (p<0.05). Experience with CI also helped.
8	Nittrouer, S. (2015)	N = 91 Age at implantation: x=22 mos, SD=18 mos	Sentences	Children with CIs did worse than NH.
9	Jacobs, E. (2016)	N = 49 Age at implantation: x=14 mos for BiCI, 18 mos for UCI (All before 3 years)	Spondee words	BiCI were the same as UCI in quiet but much better in noise. BiCI advantage larger in mainstreamed kids.
10	Taitelbaum-Swead, R. (2016)	N = 25 Age at implantation: x=16.3 mos, SD=5.6	Monosyllabic words	Lower speech perception accuracy than NH in auditory and audiovisual, higher visual speech perception than NH.
11	Lofti, Y. (2019)	N = 25 Age at implantation: R=22-28 mos (All before 2.5 yrs)	Spondee words	CI+HA helped more than just CI.
12	Nickerson, A. (2019)	N = 45 Age at implantation: x=2.3 yrs, SD=1.1	Monosyllabic words	Having HA before CI helped speech perception.
13	Lo, C. (2020)	N = 30 Age at implantation: R=0.3-2.0 yrs (All before 3.5 yrs)	Sentences	Music training improves speech perception in noise for kids with CIs.

SNR = signal-to-noise ratio, BiCI = bilaterally implanted, UCI = unilaterally implanted. HA = hearing aid, NH = normal hearing, CI+HA = bimodal fitting, R = range, x = mean, SD = standard deviation, DNR = does not report, yrs = years, mos = months. Time using CI refers to time with the first CI for BiCI users. In age at implantation column, information in parenthesis is the criteria set by researchers.

Speech perception in noise

On speech perception in noise tasks, results were also reported in many ways. Four studies compared the results of unilaterally implanted children to bilaterally implanted children. These studies all found that having two implants improved speech perception in noise. Three of these studies also found that increased experience with the cochlear implant improves speech perception overall and increases the bilateral advantage. The fourth study found that the bilateral advantage was larger in children who attended mainstream school.

Five studies compared the results of children with cochlear implants to typically hearing controls. Four of these studies found that children with cochlear implants performed worse on speech perception tasks in both quiet and noise, and that their performance in noise was significantly worse than their performance in quiet. The fifth study found that children with cochlear implants had lower speech perception accuracy in auditory and audiovisual environments, but higher speech perception in visual environments.

Two studies compared the results of children with bilateral cochlear implants to children using bimodal hearing (cochlear implant in one ear and a hearing aid in the other). One of these studies found that both bilateral implants and bimodal hearing led to worse speech perception performance than typically hearing children, but they were not significantly different from each other. The other study found that using a hearing aid in one ear before receiving a second cochlear implant improved speech perception in noise.

Finally, two studies used no comparison group. One of these studies found that the use of hearing aids improved speech perception in noise. The other found that providing music training to children with cochlear implants improves their speech perception in noise.

Discussion

Overall, factors that improved speech perception in noise were having either bilateral implants or bimodal devices and increased time using the cochlear implant. However, even when these factors were present, children with cochlear implants consistently performed worse on speech perception in noise tasks than typically hearing children. They also tended to perform significantly worse on speech perception tasks in noise than in quiet.

Many studies were excluded from this review for not reporting the age of implantation or for including participants who were implanted at the age of 4 or higher. Given that a child's age at implantation greatly influences the success of their implant, this information should always be reported. Additionally, there is a need for more research with only children implanted early. Some studies included participants implanted later than age 4 for reasons such as late diagnosis of the hearing loss. While these reasons may be valid, including these participants may affect the results of the studies.

Along with age at implantation, studies should include sign language exposure and schooling information. These factors affect the success of a cochlear implant in a given patient and how well the child is able to communicate. Exposure to sign language at a young age is often critical for deaf children to be able to learn any language. Without this language input during their critical period, some children face enormous difficulties in learning any language. Thus, this information needs to be recorded in studies that are evaluating cochlear implants. Out of the thirteen studies reviewed here, only four included information about whether the child attended mainstream school or a deaf school. In these studies, children who attended mainstream schools performed better on the speech perception in noise tests than those who attended deaf schools. This may be due to the fact that mainstream students are more used to focusing in background noise. However, in many cases, mainstream schools are the first option provided to deaf students, and deaf schools are only offered once the child fails in mainstream schools. As a result, the students attending deaf schools might be more likely to have lower levels of hearing.

Conclusions

Overall, the results of this review are consistent with the results of other studies. The factors known to improve the success of cochlear implants were also found to be true here. The review also supports the conclusion that cochlear implants are generally effective at improving speech perception in deaf children. However, the efficacy does drop significantly when children are tested in situations with background noise compared to silent conditions. Understanding the cause of this drop is critical since children are most often not in silent situations. In school, home, and other settings, children need to be able to hear in the presence of noise and discriminate which information is important and which is not.

In the future, it will be important to study whether the information presented is comprehended by participants. These studies show that, to some extent, children with cochlear implants are able to hear speech presented in noise. However, being able to hear a stimulus being played does not mean the child is able to comprehend the information they were given. In order to determine what accommodations might be necessary in mainstream school settings, ensuring comprehension is crucial.

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Appendix

Full descriptions of included studies

Paper	*First author*	*Year*	*Study size*	*Stimuli*	*SNR*	*Comparison group*	*Age at the time of testing*	*Age at implantation (yrs:mos)*	*Bilateral or unilateral*	*If bi, simultaneous or sequential*	*Hearing aid*	*Time using CI*
1	Sparreboom, M.	2010	38	Monosyllabic word	SRT found (71% correct)	BiCI vs. UCI	DNR	x=1.8 yrs, SD=0.5, R=1.1-2.7 yrs in BiCI group. x= 1.6 yrs, R=0.8-2.0 yrs in UCI group	Both	Sequential	None	DNR
2	Neuman, A.	2012	25	Sentences	Found SNR50 to be 10.25	CI vs. NH	7-12	R=1.0-3.1 yrs (All by 3 years)	6 BiCI, 1 UCI	Sequential	None	R=6-10 yrs
3	Litovsky, R.	2012	10	Spondee words	Found SRT (60 dB SPL)	BiCI vs. UCI (implanted in study)	5-10	R=1.6-3.8 yrs	UCI then implanted	Sequential	Some	R=9-79 mos
4	Caldwell, A.	2012	54	Words and phonemes	-3 dB, 0 dB, +3 dB	CI vs NH	6-7	x=21 mos, SD=13 mos	Both	DNR	Some	x=61 mos and SD=13 mos
5	Nittrouer, S.	2013	113	CVC words	0 dB, +3 dB	CI vs HA vs NH	Mean around 8	x=21 mos, SD=17 mos	28 BiCI, 19 UCI	DNR	6 in CI group had HAs	x=81 mos with CI1
6	Ching, T.	2014	70	Sentences and words	Found SRM (3 dB)	BiCI vs CI+HA	5	(All using CI by age 3)	BiCI	DNR	20 used	At least 2 yrs
7	Sparreboom, M.	2015	50	CVC words	0 dB	BiCI vs. UCI	Mean 10	x=1.8 yrs in BiCI group, x=1.9 yrs in UCI group (All before 3 years)	BiCI	Sequential	None	x=8.5 yrs

8	Nittrouer, S.	2015	91	Sentences	-3 dB, 0 dB	CI vs. NH	Mean 10	x=22 mos, SD=18 mos	27 BiCI, 18 UCI	Sequential	4 used, 4 did in past	DNR
9	Jacobs, E.	2016	49	Spondee words	Found SNR - 70% correct	BiCI vs. UCI	3-8	x=14 mos for BiCI, 18 mos for UCI (All before 3 years)	18 BiCI, 31 UCI	Simultaneous	None	At least 2 yrs
10	Taitelbaum-Swead, R.	2016	25	Monosyllabic words	0 dB	CI vs. NH	x=6.5, SD=0.9	x=16.3 mos, SD=5.6	BiCI	DNR	All used before CI	DNR
11	Lotfi, Y.	2019	25	Spondee words	65SPL	None	8-12 (x=10.96)	R=22-28 mos (All before 2.5 yrs)	UCI	N/A	Yes	DNR
12	Nickerson, A.	2019	45	Monosyllabic words	8 dB	BiCI vs. CI+HA	x-6.8yrs, SD-1.3	x=2.3 yrs, SD=1.1	30 BiCI, 15 UCI	9 simultaneous, 21 sequential	All UCI used	DNR
13	Lo, Chi Yhun	2020	30	Sentences	Started at 12 dB	None	6-9, x=7.5	R=0.3-2.0 yrs (All before 3.5 yrs)	8 BiCI, 4 UCI	DNR	All UCI used	DNR

SNR = signal-to-noise ratio, BiCI = bilaterally implanted, UCI = unilaterally implanted. HA = hearing aid, NH = normal hearing, CI+HA = bimodal fitting, R = range, x = mean, SD = standard deviation, DNR = does not report, yrs = years, mos = months. Time using CI refers to time with the first CI for BiCI users. In age at implantation column, information in parenthesis is the criteria set by researchers.