Consonant and Vowel Identification in Cochlear Implant Users Measured by Nonsense Words: A Systematic Review and Meta-Analysis

Arne Kirkhorn Rodvik, Janne von Koss Torkildsen, Ona Bø Wie, Marit Aarvaag Storaker, and Juha Tapio Silvoli

Purpose: The purpose of this systematic review and meta-analysis was to establish a baseline of the vowel and consonant identification scores in prelingually and postlingually deaf users of multichannel cochlear implants (CIs) tested with consonant–vowel–consonant and vowel–consonant–vowel nonsense syllables.

Method: Six electronic databases were searched for peer-reviewed articles reporting consonant and vowel identification scores in CI users measured by nonsense words. Relevant studies were independently assessed and screened by 2 reviewers. Consonant and vowel identification scores were presented in forest plots and compared between studies in a meta-analysis.

Results: Forty-seven articles with 50 studies, including 647 participants, thereof 581 postlingually deaf and 66 prelingually deaf, met the inclusion criteria of this study. The mean performance on vowel identification tasks for the postlingually deaf CI users was 76.8% (N = 5), which was higher than the mean performance for the prelingually deaf CI users (67.7%; N = 1). The mean performance on consonant identification tasks for the postlingually deaf CI users was higher (58.4%; N = 44) than for the prelingually deaf CI users (46.7%; N = 6). The most common consonant confusions were found between those with same manner of articulation (/k/ as /t/, /m/ as /n/, and /p/ as /t/).

Conclusions: The mean performance on consonant identification tasks for the prelingually and postlingually deaf CI users was found. There were no statistically significant differences between the scores for prelingually and postlingually deaf CI users. The consonants that were incorrectly identified were typically confused with other consonants with the same acoustic properties, namely, voicing, duration, nasality, and silent gaps. A univariate metaregression model, although not statistically significant, indicated that duration of implant use in postlingually deaf adults predict a substantial portion of their consonant identification ability.

The offering of multichannel cochlear implants (CIs) to profoundly deaf and hard-of-hearing adults and children is a well-established medical procedure today, and there are more than 600,000 CI users in the world (The Ear Foundation, 2017). The CI is offered to patients with a large variety of causes for their hearing loss and leads to a considerable improvement in hearing for the majority of users. There is, however, large variability in speech perception outcomes after cochlear implantation (Dowell, Dettman, Blamey, Barker, & Clark, 2002; Rotteveel et al., 2010; Välimaa & Sorri, 2000). Thus, it is critical to have precise measures of how well CI users can perceive different speech sounds. Such measures are important for the fitting of CIs and testing of new implant technology but also for planning and assessing the effects of listening training and speech therapy. In recent years, traditional speech perception tests using sentences and words as stimuli have increasingly produced ceiling or near-ceiling effects in CI users (Blamey et al., 2013). This may be due to a number of factors, such as shorter time of deafness before implantation,

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increased residual hearing of the implant candidates, and better hearing preservation in CI surgery. There is therefore an increasing need for more difficult tests, which provide fine-grained information on perception of consonants and vowels. Speech perception tests with nonsense words, which are more difficult than real-word tests and less reliant on prior experience with a specific language, appear to be a valuable alternative for future clinical practice and research. However, in order for nonsense word tests to be maximally useful, it is necessary to establish a baseline of the typical level of consonant and vowel perception that CI users achieve on these tests. Additionally, it is important to determine how this baseline relates to performance on other speech perception tests for both prelingually and postlingually deaf CI users. The present systematic review and meta-analysis investigates the typical performance of CI users in nonsense word tests and the influence of some clinically relevant background factors on performance in these tests.

Testing of Speech Perception in CI Users

In the first years after the advent of the CI, speech perception in CI users was assessed more thoroughly and frequently than today, as the CI technology was new and regarded as experimental by many. In these assessments, the CI users were asked to repeat monosyllabic and bisyllabic words to assess their word perception and their consonant and vowel perception and to repeat sentences with and without audiovisual support. Later, with improved implant technology, modified indications for implantation and, thus, improved hearing in the implantees, the test batteries were supplemented with sentences-in-noise tests.

The test batteries for clinical assessment of the quality of hearing in adults and children with CIs today typically consist of monosyllabic words and sentences presented in quiet and with added noise in free field, sometimes also with pure-tone audiometry in free field (Berrettini et al., 2011; Faulkner & Pisoni, 2013; Lorens et al., 2016). Usually, these tests are conducted without the possibility of lipreading, except for the poorest performers.

Testing of the speech perception of CI users is normally done with test lists of real-word monosyllables and sentences in the implantees’ native language. Because 80% of the included articles in our meta-analysis are done with English-speaking participants, we will focus on tests with English words in the following paragraph. Speech perception tests in other languages follow the same principles as the tests in English.

A common monosyllabic test is the consonant–vowel nucleus–consonant test created by Peterson and Lehiste (1962). This test is a special case of the consonant–vowel–consonant (CVC) test, which both tests the perception of real words and of speech sounds. The consonant–vowel nucleus–consonant word lists are a set of 10 lists of 50 phonemically balanced words. The test has been controlled for text-based lexical frequency across lists. The Northwestern University Auditory Test No. 6 (NU-6) monosyllable test is another test of word and speech sound recognition with monosyllables in the CVC format, consisting of 50 words and 150 speech sounds (Tillman & Carhart, 1966). Yet, another commonly used test is the Phonetically Balanced Kindergarten Word Test (Haskins, 1949). The test contains four 50-word lists and is still extensively used for assessing speech perception of children who have hearing impairment. All these three tests are commonly used in English-speaking countries and have been adapted to many other languages.

Real-word monosyllable recognition scores have been shown to have a high correlation with audiometric thresholds. In a study by Dubno, Lee, Klein, Matthews, and Lam (1995), a confidence limit for maximum word recognition scores of the NU-6 was obtained from 407 ears in a large group of young and aged subjects with confirmed cochlear hearing losses. The relationship between the pure-tone averages and the maximum word recognition scores on the basis of this study is displayed in a table by Stach (2009, p. 296).

As part of the development of implant technology, the implant companies run clinical studies regularly to test the benefits of new implants, speech processors, or speech-processing strategies. New technology is also tested in CI clinics, wherein company-supported or independent studies are conducted. Standard speech perception tests are used in testing, typically repetition of words or sentences, but also more sophisticated tests involving, for instance, consonant and vowel identification or discrimination (Carlyon, Monstrey, Deeks, & Macherey, 2014; Frijns, Briaire, De Laat, & Grote, 2002; McKay, McDermott, Vlandari, & Clark, 1992). A common test design for deciding which one of two or more speech-processing strategies gives the best speech perception for the CI user is to measure the consonant and vowel identification with each of the strategies and, then, compare the scores.

Open- or Closed-Set Tests

Speech perception is usually measured in either open- or closed-set/forced-choice test conditions, depending on what kind of information the clinician is seeking. Open-set tests provide a collection of detailed information about speech perception, listening capacity, and acoustic properties but require a substantial effort from the test leader for posttest analysis. Open-set tests have relatively small learning effects for the patient and can therefore be performed reliably at desirable intervals.

Closed-set tests are quickly performed and easily administered but give limited information about perception of individual speech sounds. The person being tested responds by pushing a button or touching a screen, and the results are interpreted automatically and instantly by a computer. However, the learning effect is considerably larger than in open-set tests because of the limited number of possible answers (Drullman, 2005). In closed-set tests, all participants should perform significantly above chance level.
Consonant and Vowel Identification

Consonants are part of a heterogeneous group of speech sounds characterized by voicing, duration, manner, and place of articulation. Phonetically, consonants are speech sounds with the air stream passing one or more constrictions on its way from the lungs through the vocal tract.

Vowels are characterized by the tongue position in the mouth cavity and by the lip-rounding. Tongue position can be high, low, back, or front. Normally, vowels are voiced, and the air stream passes frictionless along the middle of the mouth cavity while the tongue is in a static position. The vowel is the nucleus of a syllable, and a syllable can be one vowel alone or a vowel with surrounding consonants. Consonants carry more varied types of phonetic information than vowels, but many of them have lower duration and less acoustic energy. Because of this, vowel sounds are often easier to perceive than consonants, and it is widely accepted that vowels carry most of the intelligibility information in sentences (e.g., Kewley-Port, Burkle, & Lee, 2007).

Previous research has confirmed that CI users have more difficulties identifying consonants and vowels than persons with normal hearing, who typically achieve a score of 95%-100% on consonant and vowel identification tests (Kirk, Tye-Murray, & Hurtig, 1992; Sagi, Kaiser, Meyer, & Swirsky, 2009). In addition, consonant identification scores have usually been measured to be lower than vowel scores. For instance, in two Finnish studies of CI users, it was shown that 24 months after switch-on of the CIs, the average vowel recognition score was 80% and the average consonant recognition score was 71% (Välimaa et al., 2002a, 2002b).

Postlingually deaf CI users often have substantial problems identifying vowels, despite their long duration and high acoustic energy. The reason might be that the first and second formants (F1 and F2) are altered by the implant compared with what the users once used to hear. The same problem applies to the voiced consonants. Therefore, the failure rate in vowel identification by CI users may be as large as, or even larger than, the failure rate for voiced consonant identification.

Consonant and vowel identification tests provide more detailed information about the hearing of CI users than word or sentence tests. Identification of consonants and vowels can be measured both with real-word or nonsense syllable identification tests, and the scoring can be done by counting the number of correctly identified speech sounds. Other commonly used consonant and vowel identification tests have vowel–consonant–vowel (VCV) or consonant–vowel (CV) nonsense syllables as stimuli, and the consonants are typically presented in an [a] or [u] context with the target consonant in medial or initial position.

Different vowel contexts give somewhat different test results for the identification of consonants because the formant transitions of the first and second formants differ in the vowel–consonant or consonant–vowel transition phase for the different vowels and consonants. The advantages and disadvantages of the different vowel contexts have been thoroughly evaluated by Donaldson and Kreft (2006), who concluded that the choice of vowel context has small but significant effects on consonant-recognition scores for the average CI listener, with the back vowels /a/ and /u/ producing better performance than the front vowel /i/.

In typical vowel identification tests, vowels are presented in CVC or CV contexts, for example, in hVd, bVd, wVb, or bVb context, or alone. The hVd vowel-test (Hillenbrand et al., 1995; Tyler, Preece, & Lowder, 1983) has been widely used with English-speaking CI users, although vowels in hVd context form real words in English (Munson, Donaldson, Allen, Collison, & Nelson, 2003).

Although a large number of studies have been published on the subject of speech perception in CI users, there is no international consensus or standard on how to measure the identification of vowels and consonants. Several countries use nationally standardized tests for speech perception measurements. An overview of different speech perception tests (sentence identification, CVC words, and number triplets) in Danish, Dutch, (British) English, French, German, Polish, and Swedish is given in a report from the European HEARCOM project (Druhlman, 2005). However, this document only reports the use of meaningful CVC words (i.e., not nonsense words) for consonant and vowel identifications.

Consonant and Vowel Confusions

Since the early 1980s, it has been common to carry out investigations of consonant and vowel confusions to assess the benefits of CIs in speech perception (e.g., Clark et al., 1981). Acoustic similarity has usually been identified as the most important variable to explain confusions of speech sounds (Fant, 1973). Consonant and vowel confusion studies have been conducted in several languages, among them English (Baskent & Shannon, 2004; Bhattacharya & Zeng, 2007), Flemish (Van Wieringen & Wouters, 1999; Wouters & van den Bergh, 2001), and Finnish (Välimaa et al., 2002a, 2002b; Välimaa, Sorri, Laitakari, Sivonen, & Muhli, 2011).

In vowel and consonant recognition studies of postlingually deaf adult CI users, some predominant confusions have been identified. Van Wieringen and Wouters (1999)
tested vowel and consonant recognition in Flemish-speaking CI users and found that /ø/ was often confused with /æ/ and that /t/ is often confused with /l/, showing that vowel length was recognized correctly. The consonant /t/ was often confused with /l/, and /l/ was often confused with /t/, indicating that voicing and manner of articulation were recognized correctly. Munson et al. (2003) found that English-speaking CI users often confused /l/ with /l/ and /l/ with /t/, concluding that they recognized vowel length. Moreover, /d/ was confused with /g/ and /θ/ with /θ/, concluding that they recognized voicing and manner of articulation. Välimaa et al. (2011) presented longitudinal data of vowel recognition and confusion patterns in Finnish informants from before CI surgery until 4 years post-implantation. They also studied the effect of duration of profound hearing impairment before implantation and the effect of the use of different implant devices after implantation. After 4 years, the most frequent confusions were /a/ perceived as /æ/ and /l/ perceived as /l/ or /æ/, which led to the conclusion that the Finnish front vowels were the most difficult to distinguish. This is in agreement with previous studies showing that vowels with smaller spectral differences are often the most difficult to identify (Munson et al., 2003; Skinner, Fourakis, Holden, Holden, & Demorest, 1996; Van Wieringen & Wouters, 1999).

A widely used method for evaluation of the transmission of speech features is described in an article by Miller and Nicely (1955). Their method of classifying the consonant confusions by arranging them into confusion matrices (CMs) and calculating the information transmission of the linguistic features voicing, nasality, affrication, duration, and place of articulation is still in use.

Nonsense Syllable Test Words

Nonsense syllables have no meaning but are typically phonotactically legal in the language of the listener. The primary advantage of using nonsense syllables instead of real words to measure vowel and consonant identification is that the informant cannot guess which word is presented but has to rely on his or her hearing alone. Thus, the influence of other cognitive factors, such as vocabulary and inferential skills, is reduced compared with when conducting the test with real words. Consequently, nonsense syllable tests tend to be more difficult than real-word tests, as the stimuli ideally do not match any existing representation in the user’s mental lexicon.

Another advantage of nonsense syllable tests is that learning effects in multiple experiments with the same stimuli are very small compared with tests using real-word stimuli (Dubno & Dirks, 1982). Thus, it is possible to use the same nonsense syllable test for repeated examination of speech perception in the same individual to check for progress in listening ability.

Nonsense syllables are convenient to use in experiments measuring speech perception. In his classical article, Glaze (1928) showed that experiments using nonsense syllables evoke fewer associations in the participants and thus reduce between-participants variability in test results compared with experiments using real words.

Studies using nonsense syllables as stimuli can be compared across languages as long as the included speech sounds in the tests exist in both languages and a few such studies have been conducted (e.g., Pelizzoni, Cosendai, & Tinembart, 1999; Tyler & Moore, 1992).

Nonsense words used in studies of speech perception usually contain only one or, at most, two syllables to avoid the influence of possibly poor phonological working memory span on performance. However, some studies have used tests, such as the Children’s Test of Nonword Repetition (Gathercole, Willis, Baddeley, & Emstie, 1994) and other nonsense word tests primarily constructed to assess children’s working memory span and cognitive abilities, to study speech perception (Burkholder-Juhasz, Levi, Dillon, & Pisoni, 2007; Casserly & Pisoni, 2013; Nakeva Von Mentzer et al., 2015). The nonsense word test battery of Gathercole et al. (1994) contains nonsense words with two, three, four, and five syllables, but even the bisyllabic nonsense words are poorly suited to measure vowel and consonant identification, as the same vowel or consonant can be found several times in the same word in different positions and several times in the same test sequence. This makes it more complicated to measure the prevalence of consonant or vowel confusions.

Milestones in the Development of CI Technology

A significant advance in the CI technology was the transformation from single-channel to multichannel implants in the beginning of the 1980s. The single-channel implants provided limited spectral information and very rarely gave open speech understanding, as only one site in the cochlea was stimulated. Multichannel implants with four channels and more, however, provide electrical stimulation at multiple sites in the cochlea with an electrode array and can also convey frequencies covering most of the frequency range of the speech sounds. All multichannel strategies are spectral resolution strategies, as they convey spectral information to the implantees.

The stimulation strategies of the early multichannel implants were either analog or pulsatile. The main difference between the two groups of strategies is that the first employs simultaneous stimulation, whereas the latter employs sequential stimulation. A major disadvantage with the analog stimulation strategy is channel interaction, an effect that obstructs speech perception by sound distortion. This problem is less prevalent in pulsatile, nonsimultaneous stimulation. All the stimulation strategies currently used are pulsatile.

The discontinued implants from Ineraid/Symbion and from University of California, San Francisco/Storz employed the compressed analog (CA) stimulation strategy. The CA strategy was also employed by Advanced Bionics in their previous implants. Some years later, Advanced Bionics released simultaneous analog stimulation, which is a modified CA strategy. This strategy was applied until
the mid-2000s. Several clinical studies have demonstrated open speech understanding with analog stimulation strategies (e.g., Dorman, Hanning, Dankowski, Smith, & McCandless, 1989), and several studies have also compared implants running pulsatile and analog stimulation (Tyler et al., 1996; Tyler, Lowder, Parkinson, Woodworth, & Gantz, 1995; Xu, Zwolan, Thompson, & Pfingst, 2005). The results have pointed toward better speech perception with pulsatile stimulation than with analog, although there has been large variability in the outcomes. Analog strategies are not used in CI processors today.

**Variables Influencing Speech Perception in CI Users**

It has been shown in many studies that there is a large variability in speech recognition performance of CI users (Dowell et al., 2002; Rotteveel et al., 2010; Välimaa & Sorri, 2000). For a given type of implant, auditory performance may vary from 0% to 100% correct, and thus, the individual differences between CI users appear to be vastly larger than the effect of implant manufacturer. Auditory performance is here understood as the ability to discriminate, detect, identify, or recognize speech. A typical measure of auditory performance is the percentage correct score on open-set speech recognition tests. The review article by Loizou (1999) lists the following factors that have been found to affect auditory performance: the duration of deafness prior to implantation (a long duration appears to have a negative effect on auditory performance), age of onset of deafness (younger age is associated with better outcome), age at implantation (earlier implantation is associated with better outcome for prelingually deaf subjects), and duration of CI use (longer duration of CI experience is associated with better outcome). Other factors that may affect auditory performance include etiology of hearing loss, number of surviving spiral ganglion cells, electrode placement and insertion depth, electrical dynamic range of the CI, cognitive abilities, duration of hearing aid use before implantation, and signal processing strategy (Blamey et al., 2013, 2015; Rotteveel et al., 2010; Spencer, 2004; Wie, Falkenberg, Tveten, & Tomblin, 2007).

It is critical to be aware of the influence of these factors when assessing and evaluating speech perception outcomes in CI users. Furthermore, it should be kept in mind that the influence of these and other factors on speech perception may be different for prelingually and postlingually implanted children and adults.

Some studies have even found that age at implantation is not a significant predictor of speech perception outcome for prelingually deaf children (e.g., Geers, Brenner, & Davidson, 2003; Wie et al., 2007). Wie et al. (2007) found that the variations in performance on speech perception tasks could be explained by daily user time, nonverbal intelligence, duration of CI use, educational placement, and communication mode (use of sign language or spoken language). The authors explained this result by the relatively high age at implantation for the participants in the study, as only one participating child was implanted before 24 months of age.

For a group of 65 postlingually implanted adults, Plant, McDermott, van Hoesel, Dawson, and Cowan (2016) showed different factors which predicted word recognition scores for unilaterally and bilaterally implanted CI users. For the unilaterally implanted group, predictors included a shorter duration of severe-to-profound hearing loss in the implanted ear and poorer pure-tone-averaged thresholds in the contralateral ear. For the bilateral group, shorter duration of severe-to-profound hearing loss before implantation, lower age at implantation, and better contralateral hearing thresholds were associated with higher bilateral word recognition in quiet and speech reception threshold in noise.

**Transmission of Consonants and Vowels in an Implant**

The transmission of consonants and vowels in CIs is designed to reproduce a speech signal that closely resembles the original by means of electrical stimulation patterns in the CI electrode. Failure to resemble the original signal is always explained from two viewpoints: limitations in the hearing system of the implant user caused by different variables (cf. previous section) and technical limitations in the CI system. In a CI user with optimal conditions for the reception of speech, some important factors for the transmission of speech are the speech coding, the length and insertion depth of the implant, the input dynamic and input frequency range of the speech processor, and implant electrode properties.

Vowels are characterized by long duration and high energy compared with consonants, and as such, they are easily perceived by the implantees. Furthermore, vowels are characterized mainly by F1 and F2, the first two formants, which can be found in the frequency range between 200 Hz and 2500 Hz. Thus, provided the input frequency range of the implant includes frequencies as low as 200 Hz, all vowels should be possible to recognize.

For the perception of pitch, the insertion depth of the implant plays an important role. The tonotopy of the cochlea is organized with the low frequency sounds in the apical region and the high frequency sounds in the basal region. When the more apical part of cochlea is stimulated, darker pitch is received by the implantee. Thus, one should expect that users of the implants with the longest electrodes, like Med-El’s, would obtain best pitch perception. However, this is not always the case.

Some stimulation strategies are supposed to be better for the perceptions of voiced sounds than others. For example, the FSP/FS4/FS4-p strategies from Med-El will code the fundamental frequencies on the most apical electrodes in addition to running ordinary continuous interleaved sampling (CIS) stimulation. The HiRes120 strategy from Advanced Bionics is marketed as being supposed to improve the spatial precision of stimulus delivery and be more suitable for the perception of pitch and music than...
spectral envelope strategies like CIS or Advanced Combination Encoder (Wouters, Francart, & McDermott, 2015).

The microphone sensitivity in the speech processors plays an important role in the perception of soft sounds, and the higher the microphone sensitivity is, the better these speech sounds are picked up. None of the implants have problems with picking up soft speech sounds, as long as the sounds are within the input frequency range of the speech processor.

Consonants are a more heterogeneous group of speech sounds than the vowels. They can be characterized, for example, by long or short duration, by voicing or nonvoicing, or by being nasal or nonnasal. Many of the consonants, especially the unvoiced stops and fricatives, have high frequency parts, which are easily picked up by the CI speech processors. Earlier research has shown that acoustic similarity of the consonants is the most important reason for confusion (Fant, 1973), as implant users most frequently confuse consonants that are pronounced in the same manner but with a constriction in different places in the mouth cavity. Consonants that are pronounced with different manner in the same place are seldom confused. Furthermore, CI users have more trouble distinguishing between voiced consonants than between unvoiced and have the most trouble distinguishing between nasals and laterals.

Cognitive explanatory factors obviously play an important role in the perception of consonants and vowels but are outside the scope of this discussion.

Aim and Research Questions

The aim of this systematic review and meta-analysis was to examine previous research in order to investigate how well users of multichannel CIs identify consonants and vowels in tests using monosyllabic and bisyllabic nonsense words as stimuli. We wanted to ascertain the baseline of consonant and vowel identification (Fant, 1973), as implant users most frequently confuse consonants that are pronounced in the same manner but with a constriction in different places in the mouth cavity. Consonants that are pronounced with different manner in the same place are seldom confused. Furthermore, CI users have more trouble distinguishing between voiced consonants than between unvoiced and have the most trouble distinguishing between nasals and laterals.

Cognitive explanatory factors obviously play an important role in the perception of consonants and vowels but are outside the scope of this discussion.

To our knowledge, a systematic review and meta-analysis of studies on consonant and vowel identification in CI users tested by nonsense syllables has not been published before.

Method

This systematic review was conducted in accordance with the 27-item checklist in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (Moher, Liberati, Tetzlaff, & Altman, 2009).

Details of the systematic review protocol were registered with PROSPERO, the international prospective register of systematic reviews, on December 15, 2014. The protocol is available online at: http://www.crd.york.ac.uk/prospero/display_record.asp?ID=CRD42014015141.

The systematic review was performed in the following steps:

- Literature search.
- Screening of articles for inclusion and exclusion.
- Extraction of information from the articles (coding).
- Pooling of data for statistical analysis.

A flow diagram displaying the process from searching, via screening and eligibility to the final number of included articles, is shown in Figure 1. The diagram is based on a template designed by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009).

The forest plots displayed in Figures 2, 3, and 4 were generated by means of the software Comprehensive Meta-Analysis (CMA; Borenstein, Hedges, Higgins, & Rothstein, 2014).

Literature Searches

Detailed searches for primary and retrospective studies were performed in the following six databases: EMBASE, MEDLINE, PsycINFO, ERIC, Web of Science/Web of Knowledge, and Scopus. Initially, the databases Cochrane Library, Speech Bite, Sveden, Pubpsych, Proquest, Norart, Researchgate.com, and Academia.edu were also searched by the review team, but these searches returned no results.

The searches were run three times on August 13, 2014, April 6, 2015, and October 9, 2016 and were limited to peer-reviewed journal articles written in English, in Scandinavian languages (Norwegian, Swedish, and Danish), and in Finnish. The search strings consisted of two elements: (a) various terms referring to nonsense words and speech discrimination and (b) terms referring to CIs. All the search strings were truncated in order for the searches to include all conjugations of the nouns. Truncation was represented by an asterisk (*).
Figure 1. Flow diagram, searches for “nonsense words” with synonyms and “cochlear implants” with synonyms. CI = cochlear implant; EMBASE = Excerpta Medica Database; MEDLINE = Medical Literature Analysis and Retrieval System Online; PsycINFO = Psychological Information Database; ERIC = Education Resources Information Center; WOS = Web of Science. Copyright © 2009 Moher et al. (Creative Commons Attribution License).

(a) Nonsense word repetition with the synonyms non-word*, NW*, nonsense word*, pseudo word*, nonsense syllable*, pseudo syllable*, CV* word*, VC* word*, speech sound repetition*, speech sound recognition*, speech sound confusion*, speech sound discrimination*, speech sound perception*, phoneme repetition*, phoneme recognition*, phoneme confusion*, phoneme identification*, and phoneme discrimination*.

(b) Cochlear implants with the synonyms CI, cochlear prosthesis*, hearing aid*, sensory aid*, hearing instrument*, and hearing device*.

Because “cochlear implant” is an unambiguous concept, unlike “nonsense word repetition,” the number of search terms in (b) turned out to be considerably lower than in (a). The complete search syntaxes for the four Ovid databases EMBASE, MEDLINE, PsycINFO, and ERIC, as well as for Web of Science and Scopus, are listed in the Appendix.
Screening of Abstracts and Review of Full-Text Articles

The search results were imported into EndNote, v. X7.7.1 (Thompson Reuters), for removal of duplicates, books and book chapters, dissertations, editorials, systematic reviews, and articles in languages other than Danish, English, Finnish, Norwegian, and Swedish. Thereafter, the references were imported into the web-based systematic review software DistillerSR (EvidencePartners), which was used for the screening process.

Assessment of articles was performed in two phases: (a) screening of abstracts and titles and (b) full-text review of the remaining articles, as described in Figure 1. In Phase (a), two researchers (the first author, AKR, and the fourth author, MAS) independently evaluated all the identified titles and abstracts and excluded the studies missing one or both of the search terms cochlear implants and nonsense words with synonyms. Disagreements were solved by discussion or by reading the full text of the articles. Further on, the abstracts were screened by AKR for number of participants, and studies with less than three participants...
Figure 4. Forest plot of consonant identification scores for postlingually deaf cochlear implant users. The primary studies are represented by boxes, which are bounded by the confidence interval (CI) for the effect sizes in each study. The effect sizes are measured in percent.

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<th>Outcome</th>
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<tr>
<td>Postlingual consonant score</td>
<td>Cosendai &amp; Pelizzone, 2001</td>
<td></td>
</tr>
</tbody>
</table>
were excluded, as case studies with one or two participants did not fit into the methodology of the systematic review.

In Phase (b), full-text articles were reviewed according to exclusion Criteria IV and V in Figure 1. During this phase, some of the articles were also excluded according to Criterion I, II, or III when this applied. Further details on the inclusion and exclusion criteria are found in the subsequent paragraphs.

Inclusion Criteria

Inclusion criteria were based on the Participants, Intervention, Control, Outcomes, and Study designs strategy (Santos, Pimenta, & Nobre, 2007; see Table 1).

The included articles described studies with three participants or more. We focused on the outcome of consonant and vowel identification tests measured by nonsense words in free field 6 months or more after implantation. If use of repeated measures in longitudinal studies was reported in the article, we registered the most recent nonsense word scores. If different nonsense word tests for the same groups of participants were used, for example, in Kirk et al. (1992), we included the test that provided results with the highest score. If the article referred to other articles by the same authors for more details about the tests, we extracted the necessary information from these.

Exclusion Criteria

- Studies on participants with single-channel CIs were excluded. This was based on research showing that implants need at least four channels to provide adequate speech perception in quiet (Cohen, Waltzman, & Fisher, 1993; Tyler et al., 1988).
- Studies measuring consonant or vowel score by real-word stimuli and not by nonsense syllables were excluded.
- Studies measuring consonant or vowel score by nonsense words with three or more syllables were excluded, as it is difficult to disentangle effects of working memory span from hearing when interpreting these results. In addition, the same target consonants or vowels are often presented more than once in such multisyllable test words.
- Studies assessing the identification of less than about 50% of the national inventory of vowels and consonants were excluded, as these studies presented vowel and consonant identification scores on the basis of too few consonants and vowels to represent the phoneme inventory of this language. For instance, there are 20–24 consonants in English, depending on the dialect, and for the study to be included, at least half of these had to be used to calculate a consonant identification score.
- Studies in which means and standard deviations of the consonant and vowel identification score were not reported, only reported graphically in diagrams, or could not be calculated from confidence intervals or standard errors were excluded. For those excluded studies published less than 10 years ago, we wrote to the corresponding author to ask for the raw data from the study. Studies from which the raw data were received were included in the meta-analysis.
- Studies in which nonsense words were presented live instead of recorded were excluded because of less expected consistency in the test results than in recorded materials (Mendel & Owen, 2011).
- Studies in which the stimuli were presented with lip-reading support were excluded.
- Studies using synthesized or electronically generated test stimuli were excluded.
- Studies displaying speech sound scores not separated into a vowel and a consonant score were excluded.
- Studies in which the identification score for consonants was only reported as categories according to consonant properties like place, manner, or voicing (e.g., Nelson, Van Tasell, Schroder, Soli, & Levine, 1995) were excluded.
- In those cases where different articles were based on the same study participants and/or the same data, all but one of these articles were excluded. The article that included the highest number of participants was selected for further analysis.
- Studies including participants with a contralateral hearing aid in addition to an implant were excluded unless it was clearly stated in the article that the

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
<th>Application of the criteria on the present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>Participants</td>
<td>Adults and/or children with one or two multichannel CIs</td>
</tr>
<tr>
<td>I</td>
<td>Intervention</td>
<td>None</td>
</tr>
<tr>
<td>C</td>
<td>Control</td>
<td>Studies included both with and without control group</td>
</tr>
<tr>
<td>O</td>
<td>Outcomes</td>
<td>Consonant and/or vowel identification scores, measured by nonsense words</td>
</tr>
<tr>
<td>S</td>
<td>Study designs</td>
<td>Cross-sectional studies, longitudinal studies, case studies (N ≥ 3)</td>
</tr>
</tbody>
</table>

Note. PICOS = Participants, Intervention, Control, Outcomes, and Study designs (adapted from Santos, Pimenta, & Nobre, 2007); CI = cochlear implant.
benefit of the implant was better than the benefit of the hearing aid.

Risk of Publication Bias

Risk of publication bias was commented on qualitatively and by inspection of funnel plots generated in CMA. A symmetrical funnel plot could indicate the absence of publication bias. However, an asymmetrical funnel plot could indicate several conditions, for instance, heterogeneity, publication bias, or chance, and the interpretation of the asymmetry with regard to publication bias has been highly disputed in previous research (Lau, Ioannidis, Terrin, Schmid, & Olkin, 2006; Sterne et al., 2011). Although it is common in meta-analyses to correct the asymmetry in funnel plots by the "Trim-and-fill" method, we chose not to make use of this technique in our study, as there are substantial methodological problems related to it (Lau et al., 2006). Effect sizes may be underestimated when publication bias does not exist and overestimated when publication bias does exist, and thus, it can be argued that the method is inadequate as a corrective technique (Simonsohn, Nelson, & Simmons, 2014). Therefore, we chose not to draw definite conclusions about publication bias in the case of asymmetry.

Quality Assessment

Publications considered to be of weak overall quality by the review team were excluded from the systematic review. These quality criteria were

• inconsistent presentation of results;
• errors in the analyses; and
• lack of transparency, for example, missing description of the study methods.

Selection and Coding of Data

A pilot coding was performed on 11 articles by MAS, to test the strength of the categories in the coding form. After this, an evaluation of the pilot coding was performed by the review team to develop the final coding form, in which the selection of coding parameters was done based on our research questions. The following data were extracted from the articles: author, title of article, publication year, journal, aim, language, and study design, and absence or presence of a control group. For studies including participants with an implant, the following measures were coded: number of participants; number of postlingually/prelingually implanted participants; number of participants with auditory neuropathy spectrum disorder; implant type; speech-processing strategy; age at testing; age at implantation; duration of implant use; duration of deafness before implantation; age at onset of deafness; stimulation level; number of unilaterally or bilaterally, sequentially, or bimodally implanted participants; identification score for vowels; most confused vowel; identification score for consonants; most confused consonant; monosyllable real-word identification score; and score from postoperative audiometric measurements.

For participants with normal hearing serving as control groups, the following measures were coded: number of participants, identification score for vowels, most confused vowel, identification score for consonants, most confused consonant, and monosyllable real-word identification score. The data were extracted to the form by AKR.

Strategy for Data Synthesis

Both aggregate and individual participant data were used. We used quantitative methodology on the included studies, which were sufficiently homogeneous. Vowel and consonant identification scores and vowel and consonant confusions were compared between studies and between languages, despite cross-linguistic differences (Tyler & Moore, 1992).

Analysis

Our meta-analysis included studies reporting means and standard deviations. A random effects model was chosen over a fixed effects model to average the effect sizes across studies, as this does not assume a shared common true effect (Borenstein, Hedges, Higgins, & Rothstein, 2009).

Research Question 1, “What are the typical vowel and consonant identification scores in cochlear implanted participants when measured with nonsense syllables, and how do the typical vowel and consonant identification scores differ between prelingually and postlingually deaf implantees?” was answered statistically by pooling of the studies in CMA. Individual consonant and vowel identification scores were weighted by the random effects model, averaged across studies and presented as forest plots in Figures 2, 3, and 4.

To answer Research Question 2, “Which consonants and vowels are most frequently confused by CI users, and which consonants and vowels are most frequently identified correctly?” we constructed meta CMs to display the three most common vowel and consonant confusions, from the 11 studies in which this information was available. In some articles, this information was given qualitatively, and in these cases, our presentation of the results was also given qualitatively.

To answer Research Question 3, only users with post-lingual deafness were included in the analysis, as very few studies reported consonant and vowel scores for the pre-lingually deaf group. We performed a univariate regression analysis with the weighted mean consonant identification score against duration of CI use. Real-word monosyllable score and vowel identification score were omitted as independent and dependent variables in the analyses because this was only reported in 17 studies and 6 studies, respectively. We obtained beta regression coefficients to characterize the univariate relationship and explained the percentage of between-studies variance by using $R^2$, which quantifies the proportion of variance explained by the covariates (Borenstein et al., 2009).
Results

Study Characteristics

The results are based on analyses of the 50 studies reported in the 47 included articles, and the study characteristics are summarized in Table 2 and below. The articles that met our inclusion criteria were published between 1989 and 2016. Three of these articles were treated as two independent studies each in the meta-analysis, with different participants in each study (Kirk et al., 1992; Munson et al., 2003; Tyler & Moore, 1992). In 38 of the studies, the participants were speaking English, and 32 of these studies had participants with American English as their mother tongue. In eight of the remaining nine studies, the participants spoke either Flemish, French, German, Italian, or Japanese. In the final study, the participants reportedly spoke one or seven mother tongues, namely, Albanian, French, German, Italian, Russian, Spanish, and Swahili (Pelizzzone et al., 1999). The large majority of participants (581 of 647) were reported as postlingually deaf and the rest (66) as prelingually deaf. As the criteria for prelingual and postlingual deafness differed between studies, and often were not reported, we used the studies’ own report of prelingual and postlingual deafness in our statistics.

Six hundred thirteen participants were unilaterally implanted, 10 bilaterally and 24 bimodally. The number of participants per study varied between three and 56. Three articles described CI users with a hearing aid on the contralateral ear (bimodal users; Gani, Valentini, Sigrist, Kos, & Boex, 2007; Incerti, Ching, & Hill, 2011; Sheffield & Zeng, 2012). From these articles, we included in our meta-analysis only the results obtained without a hearing aid. In one of the articles, the participants’ vowel perception was tested both with vVb and with bVb words (Kirk et al., 1992). According to our inclusion criteria stating that the participants should not be represented in the material more than once, we chose to use the bVb words in our analyses, as these gave the highest mean score of vowel perception.

The participants used implants from the CI manufacturers Advanced Bionics, Cochlear, Digisonic/Neurelec, Ineraid/Symbion, Laura, and Med-El. Many studies reported results from participants with implants from more than one manufacturer and results from studies in which one implant used several stimulation strategies, thus it was not always possible to pool results per implant model or per stimulation strategy.

The mean age at onset of deafness was 31.6 years (SD = 18.0 years, range = 2.6–52.4 years), reported in 28 studies, and the duration of profound deafness before CI was 14.8 years (SD = 8.1 years, range = 2.7–38.9 years), reported in 29 studies.

Only two of the included studies had children or adolescents as participants (Arisi et al., 2010; Tyler, 1990). In a study by Tyler (1990), the five children who participated had a mean age of 8.5 years (SD = 1.6 years, range = 6.8–10.3 years) and obtained a consonant identification score of 30% (SD = 13.2%, range = 19%–50%). In a study by Arisi et al. (2010), 45 adolescent participants had a mean age of 13.4 years (SD = 2.6 years, range = 11–18 years) and obtained a consonant identification score of 53.5%.

Research Question 1: What are the Typical Vowel and Consonant Identification Scores in CI Users When Measured by Nonsense Syllables, and How Do the Typical Vowel and Consonant Identification Scores Differ in Prelingually and Postlingually Deaf Implantees?

Table 3 shows the vowel and consonant identification scores for the studies with prelingually deaf participants, the studies with postlingually deaf participants, and for the whole sample of 50 studies. All scores are weighted by the random effects model (Borenstein et al., 2009). Only five studies reported scores on vowel identification for the postlingually deaf (Cosendai & Pelizzzone, 2001; Gani et al., 2007; Ito, Tsuji, & Sakakihara, 1994; Kirk et al., 1992; Pelizzzone et al., 1999). Four of these studies (including 30 participants) reported both consonant and vowel identification scores. For the prelingually deaf, a vowel score for one CI user was reported in only one article, which also reported a consonant score for the same user (Gani et al., 2007). Another article reported the consonant score of one prelingually deaf CI user (Bhattacharya & Zeng, 2007). These scores could not be included in the analyses because of an SD of 0. Finally, vowel identification scores for the normal-hearing group were only calculated in one study, and a mean score of 98.3% (SD = 1.0%) was reported (Kirk et al., 1992).

Consonant identification scores were reported in 46 articles (48 studies). Four of these articles had to be excluded because the consonant scores could not be split into one score for the prelingually deaf and one for the postlingually deaf (Kirk et al., 1992; Munson et al., 2003; Stacey et al., 2010; Van Wieringen & Wouters, 1999). Consonant identification scores were not reported for any of the normal-hearing control groups, which were included in 13 of the studies. In many of these studies, the control group was used for calibrating the consonant and vowel identification test in the local dialect. This was done by requiring a score of 95% or higher on the test by the control group, before the test could be used for testing cochlear-implanted participants. If the score for the control group turned out to be lower than the limit set in the study, the consonant identification test was modified to get the score above the limit, for instance, by removing nonsense syllables with high failure rates from the test, for example, certain test words pronounced in a dialect little known to the participants.

In Figures 2, 3, and 4, the vowel and consonant identification scores are presented as forest plots, showing the weighted mean and the 95% confidence interval for each study, arranged in ascending order. Ceiling effects were observed in the individual scores of the included studies, especially in the vowel scores.

Only five studies reported consonant identification scores for both the prelingually and postlingually deaf CI
<table>
<thead>
<tr>
<th>Authors</th>
<th>N</th>
<th>CI</th>
<th>Language of participants</th>
<th>Stimulus context</th>
<th>No. of consonants and vowels in the test</th>
<th>Age (years) of implantation, M (SD)</th>
<th>Duration (years) of implant use, M (SD)</th>
<th>Speech sound score (%)</th>
<th>Monosyllables</th>
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<tbody>
<tr>
<td>Arisi et al., 2010</td>
<td>45</td>
<td>0</td>
<td>Italian</td>
<td>VCV</td>
<td>—</td>
<td>13.4 (2.6)</td>
<td>&gt; 3</td>
<td>53.5 (33.6)</td>
<td>—</td>
</tr>
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<td>Baskent &amp; Shannon, 2004</td>
<td>6</td>
<td>0</td>
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<td>aCa</td>
<td>20</td>
<td>38.3 (13.6)</td>
<td>3.0 (1.5)</td>
<td>63.6 (21.7)</td>
<td>—</td>
</tr>
<tr>
<td>Bhattacharya &amp; Zeng, 2007</td>
<td>7</td>
<td>6</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
<td>63.3 (10.7)</td>
<td>3.4 (1.8)</td>
<td>68.4 (23.6)</td>
<td>—</td>
</tr>
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<td>4</td>
<td>0</td>
<td>English (Australia)</td>
<td>aCa</td>
<td>16</td>
<td>54.0 (21.6)</td>
<td>3.3 (2.6)</td>
<td>71.1 (20.9)</td>
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<td>4</td>
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<td>VCV</td>
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<td>7.0 (5.0)</td>
<td>66.0 (17.0)</td>
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<td>French</td>
<td>aCa, V</td>
<td>14 (VCV), 7 (V)</td>
<td>32.0 (12.8)</td>
<td>10.0 (4.4)</td>
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<td>14</td>
<td>English (USA)</td>
<td>VCV</td>
<td>20</td>
<td>62.5 (13.9)</td>
<td>3.8 (3.5)</td>
<td>49.6 (26.7)</td>
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<td>20</td>
<td>0</td>
<td>English (USA)</td>
<td>aCa, iCi, uCu, Ca, Ci</td>
<td>14 (aCa), 7 (V)</td>
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<td>3.3 (3.6)</td>
<td>59.8 (13.9)</td>
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<td>English (USA)</td>
<td>aCa</td>
<td>16</td>
<td>Adult</td>
<td>—</td>
<td>58.1 (9.8)</td>
<td>—</td>
</tr>
<tr>
<td>Dorman &amp; Loizou, 1996</td>
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<td>0</td>
<td>English (USA)</td>
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<td>&gt; 4</td>
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<td>1.0 (0.6)</td>
<td>52.7 (17.2)</td>
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<td>19</td>
<td>5</td>
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<td>aCa</td>
<td>14</td>
<td>59.0 (13.3)</td>
<td>2.6 (2.2)</td>
<td>53.2 (14.4)</td>
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<td>0</td>
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<td>aCa</td>
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<td>46.9 (9.3)</td>
<td>8.6 (2.5)</td>
<td>59.1 (20.3)</td>
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<td>English (USA)</td>
<td>aCa</td>
<td>16</td>
<td>53.0 (12.4)</td>
<td>5.3 (2.3)</td>
<td>67.8 (11.7)</td>
<td>—</td>
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<td>Galvin et al., 2007</td>
<td>11</td>
<td>9a</td>
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<td>20</td>
<td>49.0 (14.9)</td>
<td>7.3 (4.8)</td>
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<td>Gani et al., 2007</td>
<td>4</td>
<td>0</td>
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<td>aCa, V</td>
<td>14 (aCa), 7 (V)</td>
<td>46.8 (15.3)</td>
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<td>French (France)</td>
<td>VCV</td>
<td>16</td>
<td>49.3 (8.7)</td>
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<td>Guevara et al., 2016</td>
<td>16</td>
<td>0</td>
<td>French (France)</td>
<td>VCV</td>
<td>16</td>
<td>48.8 (14.2)</td>
<td>5.1 (3.7)</td>
<td>42.5 (21.6)</td>
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<td>Han et al., 2016</td>
<td>10</td>
<td>11a</td>
<td>English (Australia)</td>
<td>aCa</td>
<td>16</td>
<td>45.1 (18.2)</td>
<td>6.1 (4.0)</td>
<td>74 (21.1)</td>
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<td>15</td>
<td>0</td>
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<td>4.2 (–)</td>
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<td>Japanese</td>
<td>V, aCa</td>
<td>5 (V), 13 (aCa)</td>
<td>Adult</td>
<td>87.7 (10.5)</td>
<td>41.7 (11.2)</td>
<td>—</td>
</tr>
<tr>
<td>Kirk et al., 1992, Sample A</td>
<td>10</td>
<td>12</td>
<td>English (USA)</td>
<td>wVb, bVb</td>
<td>8</td>
<td>47.3 (9.7)</td>
<td>1.7 (1.3)</td>
<td>50.5 (4.8)</td>
<td>22.8 (17.0) NU-6</td>
</tr>
<tr>
<td>Kirk et al., 1992, Sample B</td>
<td>11</td>
<td>12</td>
<td>English (USA)</td>
<td>wVb, bVb</td>
<td>8</td>
<td>53.4 (17.3)</td>
<td>1.8 (4.6)</td>
<td>52 (4.0)</td>
<td>14.2 (16.1) NU-6</td>
</tr>
<tr>
<td>McKay et al., 1992</td>
<td>4</td>
<td>0</td>
<td>English (Australia)</td>
<td>aCa</td>
<td>12</td>
<td>45.0 (16.9)</td>
<td>2.7 (1.7)</td>
<td>77 (9.7)</td>
<td>57.6 (26.6) NU-6</td>
</tr>
<tr>
<td>Meyer et al., 2003</td>
<td>26</td>
<td>0</td>
<td>English (Australia)</td>
<td>aCa</td>
<td>24</td>
<td>Adult</td>
<td>&gt; 11 months</td>
<td>42.3 (22.2)</td>
<td>38.0 (24.5) CNC</td>
</tr>
<tr>
<td>Munson et al., 2003, Sample A</td>
<td>14</td>
<td>0</td>
<td>English (USA)</td>
<td>aCa</td>
<td>19</td>
<td>41.4 (10.3)</td>
<td>3.6 (3.5)</td>
<td>78.5 (6.1)</td>
<td>66.6 (17.7) NU-6</td>
</tr>
<tr>
<td>Munson et al., 2003, Sample B</td>
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<td>0</td>
<td>English (USA)</td>
<td>aCa</td>
<td>19</td>
<td>55.1 (12.2)</td>
<td>4.3 (4.1)</td>
<td>46.9 (13.0)</td>
<td>26.8 (18.5) NU-6</td>
</tr>
<tr>
<td>Nie et al., 2006</td>
<td>5</td>
<td>0</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
<td>35.8 (12.8)</td>
<td>4.6 (1.1)</td>
<td>64 (14.7)</td>
<td>—</td>
</tr>
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<td>0</td>
<td>Albanian, French, German, Italian, Russian, Spanish, Swahili</td>
<td>aCa, V</td>
<td>14 (aCa), 7 (V)</td>
<td>43.3 (16.5)</td>
<td>5.1 (3.0)</td>
<td>78.3 (17.2)</td>
<td>65.6 (24.1)</td>
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</tbody>
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Table 2. (Continued).

<table>
<thead>
<tr>
<th>Authors</th>
<th>N</th>
<th>Language of participants</th>
<th>Stimulus context</th>
<th>No. of consonants and vowels in the test</th>
<th>Age (years) of implantation, M (SD)</th>
<th>Duration (years) of implant use, M (SD)</th>
<th>Speech sound score (%)</th>
<th>Monosyllables</th>
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<tbody>
<tr>
<td>Sagi et al., 2009</td>
<td>11</td>
<td>English (USA)</td>
<td>aCa</td>
<td>16</td>
<td>50.4 (14.5)</td>
<td>3.6 (1.9)</td>
<td>43.1 (22.6)</td>
<td>38.6 (21.1) CNC</td>
</tr>
<tr>
<td>Shafiro et al., 2011</td>
<td>17</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
<td>55.0 (11.2)</td>
<td>3.2 (2.1)</td>
<td>51 (24)</td>
<td>51.8 (30.5) CNC</td>
</tr>
<tr>
<td>Shallop et al., 1992</td>
<td>7</td>
<td>English (USA)</td>
<td>aCa</td>
<td>14</td>
<td>58.4 (14.0)</td>
<td>1 (0)</td>
<td>50.6 (19.0)</td>
<td>21.2 (12.9) NU-6</td>
</tr>
<tr>
<td>Shannon et al., 2011</td>
<td>7</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
<td>48.3 (9.1)</td>
<td>1.0 (0.3)</td>
<td>62.7 (7.3)</td>
<td>66.4 (17.9) CNC</td>
</tr>
<tr>
<td>Shannon et al., 2011 (b)</td>
<td>6</td>
<td>English (USA)</td>
<td>aCa</td>
<td>14</td>
<td>52.2 (11.1)</td>
<td>5.0 (2.9)</td>
<td>67.6 (18.5)</td>
<td>44 (22.5) NU-6</td>
</tr>
<tr>
<td>Sheffield &amp; Zeng, 2012</td>
<td>8</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
<td>58.6 (11.4)</td>
<td>4.4 (2.0)</td>
<td>59.1 (5.2)</td>
<td>—</td>
</tr>
<tr>
<td>Singh et al., 2009</td>
<td>5</td>
<td>English (USA)</td>
<td>aCa</td>
<td>20</td>
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<td>3.0 (2.6)</td>
<td>72.6 (16.1)</td>
<td>—</td>
</tr>
<tr>
<td>Skinner, Arndt, et al., 2002</td>
<td>12</td>
<td>English (USA and Australia)</td>
<td>aCa</td>
<td>14</td>
<td>50.9 (22.6)</td>
<td>Short</td>
<td>64.6 (14.6)</td>
<td>—</td>
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<td>Stacey et al., 2010</td>
<td>11</td>
<td>English (UK)</td>
<td>aCa</td>
<td>20</td>
<td>49.1 (19.5)</td>
<td>5.7 (2.7)</td>
<td>39.8 (18.8)</td>
<td>—</td>
</tr>
<tr>
<td>Svisky et al., 2011</td>
<td>28</td>
<td>English (USA)</td>
<td>aCa</td>
<td>24</td>
<td>49.7 (15.9)</td>
<td>3.3 (2.5)</td>
<td>45.1 (20.7)</td>
<td>—</td>
</tr>
<tr>
<td>Teoh et al., 2003</td>
<td>15</td>
<td>English (USA)</td>
<td>aCa</td>
<td>24</td>
<td>52.9 (12.7)</td>
<td>3.6 (1.8)</td>
<td>46.7 (18.1)</td>
<td>—</td>
</tr>
<tr>
<td>Throckmorton &amp; Collins, 1999</td>
<td>7</td>
<td>English (USA)</td>
<td>aCa</td>
<td>14</td>
<td>54.6 (11.6)</td>
<td>6.9 (2.8)</td>
<td>34 (14.2)</td>
<td>14.9 (10.7) NU-6</td>
</tr>
<tr>
<td>Tye-Murray et al., 1990</td>
<td>5</td>
<td>English (USA)</td>
<td>iCi</td>
<td>14</td>
<td>Adult &gt; 10 months</td>
<td></td>
<td>41 (13.1)</td>
<td>27.6 (13.2) NU-6</td>
</tr>
<tr>
<td>Tye-Murray et al., 1996</td>
<td>40</td>
<td>English (USA)</td>
<td>aCa</td>
<td>13</td>
<td>51.5 (-)</td>
<td>3.6 (2.2)</td>
<td>66 (20)</td>
<td>—</td>
</tr>
<tr>
<td>Tyler, 1990</td>
<td>5</td>
<td>English (Australia)</td>
<td>iCi</td>
<td>13</td>
<td>7.4 (1.9)</td>
<td>1.1 (0.6)</td>
<td>30 (13.2)</td>
<td>16 (20.3) PBK</td>
</tr>
<tr>
<td>Tyler &amp; Moore, 1992, Sample A</td>
<td>10</td>
<td>German</td>
<td>iCi</td>
<td>13</td>
<td>43.8 (9.5)</td>
<td>2.0 (0.6)</td>
<td>31.1 (7.0)</td>
<td>—</td>
</tr>
<tr>
<td>Tyler &amp; Moore, 1992, Sample B</td>
<td>19</td>
<td>English (USA)</td>
<td>iCi</td>
<td>13</td>
<td>37.5 (13.5)</td>
<td>2.4 (2.8)</td>
<td>43.9 (10.6)</td>
<td>—</td>
</tr>
<tr>
<td>Van Wieringen &amp; Wouters, 1999</td>
<td>25</td>
<td>Flemish</td>
<td>aCa</td>
<td>16</td>
<td>43.4 (14.2)</td>
<td>2.1 (1.4)</td>
<td>33 (13)</td>
<td>—</td>
</tr>
<tr>
<td>Wouters &amp; van den Bergh, 2001</td>
<td>4</td>
<td>Flemish</td>
<td>aCa</td>
<td>16</td>
<td>39.8 (10.4)</td>
<td>2.0 (1.4)</td>
<td>63.3 (7.9)</td>
<td>—</td>
</tr>
</tbody>
</table>

Note. The means and standard deviations are given with one decimal, except when the included articles reported these values without decimals. Em dashes indicate data not obtained. CI = cochlear implant; NH = normally hearing; VCV = vowel–consonant–vowel; aCa = a–Consonant–a; V = Vowel; iCi = i–Consonant–i; uCu = u–Consonant–u; Ca = Consonant–a; Ci = Consonant–i; Cu = Consonant–u; NU-6 = The Northwestern University Auditory Test No. 6; CNC = the consonant–vowel nucleus–consonant test; wVb = w–Vowel–b; bVb = b–Vowel–b; PBK = The Phonetically Balanced Kindergarten Word Test.

aNot tested with the consonant test. bTests performed using a CI simulator and the test results therefore not included.
users, and no studies reported vowel identification scores for both groups. Consonant identification scores for the postlingually deaf users were on average 10.9% better than for the prelingually deaf users (SD = 39.7%, range = −22.5%–47.5%, z(5) = 0.61). This difference in scores was not statistically significant (p = .54, df = 4). Hence, it is unclear whether there is a difference in consonant perception between prelingually and postlingually deaf CI users.

Research Question 2: Which Consonants and Vowels are Most Frequently Confused by CI Users, and Which Consonants and Vowels are Most Frequently Identified Correctly?

Vowel Confusions
Details on individual vowel confusions were reported in only one of the included articles (containing two studies; Kirk et al., 1992) but were based on quantitative data from 27 CMs. This article reports results from participants with normal hearing and two groups of CI users: Ineraid and Nucleus-users. Vowel stimuli were given both in bVb context and in wVb context. Identifications and misidentifications were reported qualitatively, and for the subjects with normal hearing, only a few errors were made. In the bVb context, vowel identification scores were somewhat lower than in the bVb context for both implants. In summary, the long vowels /iː, æ, aː/, and /uː/ were seldom misidentified, but the short vowels /i, e, a/, and /u/ were often confused with other short vowels. /i/ was sometimes, however, also confused with /aː/ in wVb context. Additionally, a higher number of short vowels were confused in the wVb context than in the bVb context.

Consonant Confusions
Details about consonant confusions were reported in 13 of the included articles (15 studies; Donaldson & Kreft, 2006; Dorman & Loizou, 1996; Dorman et al., 1990; Doyle et al., 1995; Incerti et al., 2011; McKay et al., 1992; Munson et al., 2003; Pelizzzone et al., 1999; Sagi et al., 2009; Teoh, Neuburger, & Svirsky, 2003; Tyler, 1990; Tyler & Moore, 1992; Van Wieringen & Wouters, 1999). In 11 of these articles, the consonant confusions were reported in CMs. Table 4 gives an overview of these 11 articles. Detailed results of the three most frequently correctly identified consonants from the 11 articles are shown in Table 5, and details about the most common consonant confusions from the 11 articles are presented in a meta-CM in Table 6. Because of the low number of articles presenting CMs (11), we chose to base our study’s matrices on the nine consonants that were used in all the 15 studies, /b, d, p, t, k, n, m, s/, and /l/. We also chose to pool articles reporting studies conducted in different languages (Australian English, American English, and Flemish) and to pool those with different kinds of stimuli, Cu, Ci, Cu, aCu, iCi, and uCu. We also pooled the only article, which included children as participants (Tyler, 1990) with the remaining articles.

In two studies (Donaldson et al., 1990; Munson et al., 2003), the participants were divided into poor and better performers; in one study, the participants were divided into poor, intermediate, and better performers (Van Wieringen & Wouters, 1999); and in two studies, the participants were divided into three groups according to type of implant (Doyle et al., 1995) or according to native language of participants (Tyler & Moore, 1992). In each of these studies, the data from the CM of each group were plotted into the table and the meta-CM. Thus, a total of 17 CMs were pooled into Table 5 and the meta-CM in Table 6.

In three of the articles, several consonant identification tests were given to the same participants. We chose the better of the two outcomes when two speech processors were compared (Dorman & Loizou, 1996; McKay et al., 1992). We chose the outcomes on the basis of use of CI alone if one CM was made based on the CI alone and one on CI + hearing aid (Incerti et al., 2011). In one article (Donaldson & Kreft, 2006), the consonant identification tests were performed in six contexts, Cu, Ci, Cu, aCu, iCi, and uCu, and averaged over all conditions. We included the pooled data in our analyses. When several CMs were presented, obtained with and without background noise and with and without lipreading (Incerti et al., 2011), testing in quiet and auditory-only condition was chosen.

As Table 5 shows, the consonants that were most frequently identified correctly were the unvoiced stops /t/ and /k/.

The meta-CM in Table 6 shows that the most frequent confusions were /k/ confused with /t/ and /m/ confused with /n/.

### Table 3. Means, standard deviations, and ranges of the study variables for the prelingually and postlingually deaf CI users.

<table>
<thead>
<tr>
<th>Study variables</th>
<th>Postlingually deaf</th>
<th>Prelingually deaf</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (SD) (%)</td>
<td>N</td>
<td>Range (%)</td>
</tr>
<tr>
<td>Consonant score</td>
<td>58.4 (26.3)</td>
<td>44</td>
<td>18.7–91.6</td>
</tr>
<tr>
<td>Vowel score</td>
<td>76.8 (26.5)</td>
<td>5</td>
<td>50.5–95.0</td>
</tr>
<tr>
<td>Real-word monosyllable score</td>
<td>40.1 (16.6)</td>
<td>14</td>
<td>14.9–66.6</td>
</tr>
</tbody>
</table>

Note. In three of the studies, the real-word monosyllable scores could not be separated into separate scores for the groups of prelingually and postlingually deaf CI users. Em dashes indicate data not obtained. CI = cochlear implant.
Research Question 3: (a) To What Extent are Age at Implantation, Duration of Implant Use, and Real-Word Monosyllable Score Associated With Variations in Consonant and Vowel Identification Performance in Nonsense Syllable Tasks for Prelingually Deaf CI Users? (b) To What Extent are Duration of Implant Use and Real-Word Monosyllable Score Associated With Variations in Consonant and Vowel Identification Performance in Nonsense Syllable Tasks for Postlingually Deaf CI Users?

(a) The weighted scores of age at implantation and duration of implant use for the prelingually and postlingually deaf CI users are reported in Table 7. The monosyllable scores are reported in Table 3. Because only six studies report results for prelingually deaf CI users, a bivariate metaregression was not carried out, and Research Question 3 (a) could not be answered.

(b) Only five studies reported a vowel identification score for the group of postlingually deaf. This is too few to provide an adequate representation of the included studies, and further analyses were therefore not performed on this group. The vowel identification scores can be examined in Table 3.

We decided to omit monosyllable scores from the multiple regression model with postlingually deaf CI users due to a small number of studies (N = 14). A univariate regression model was then constructed with the moderator variable duration of implant use and the independent variable consonant identification score. The results of the univariate regression were β = 2.6, SE = 1.9, 95% confidence interval = [−0.22, 5.3], z = 1.81, and not significant (p = .071). The proportion of total between-studies variance explained by the model was $R^2 = .59$, $N = 36$.

Publication Bias

In order to optimize the quality of our included study sample, we have only included peer-reviewed, published studies written in English, Finnish, and in Scandinavian languages. Although we performed searches in a number of grey material databases in the beginning of our systematic review process, without finding any relevant studies, some unpublished and even published research may still be missing from our searches. Also, relevant studies may have experienced delayed publishing for various reasons. Thus, there might be some publication bias in our systematic review.

By visual inspection of the funnel plot for the consonant identification scores of the postlingually deaf, we noticed that the studies were slightly scattered to the left of the mean of the funnel plot. The asymmetry in the funnel plot may be a sign of publication bias, heterogeneity, or chance.

Discussion

The purpose of this systematic review and meta-analysis is to establish a baseline of the vowel and consonant identification scores in prelingually and postlingually...
deaf users of multichannel CIs tested with CVC and VCV nonsense syllables.

The mean consonant and vowel identification scores for the prelingually and postlingually deaf CI users show that performance was well below ceiling for both groups and that there were higher scores for vowels than for consonants. The mean differences between the consonant identification scores for the prelingually and postlingually deaf CI users were not statistically significant.

Details of the vowel confusions were given qualitatively and in only one article. Details of the consonant confusions were given in CMs in 11 articles. Our meta-CM showed that the most frequently confused consonants were /k/ confused with /t/ and /m/ confused with /n/.

In a univariate regression model between duration of implant use and consonant identification score for postlingually deaf CI users, duration of implant use explained 59% of the variance in effect sizes. The model was not statistically significant (p = .071).

Research Question 1: Typical Vowel and Consonant Identification Scores

We could not draw definite conclusions about differences in consonant identification between prelingually and postlingually deaf CI users because of the large difference in sample size between the groups (six studies with prelingually deaf and 44 studies with postlingually deaf). The same reason applies to why Research Question 1 could not be answered with regard to vowel identification score, as only one article with one participant reported a vowel score of prelingually deaf CI users and five articles reported vowels scores of postlingually deaf CI users.

Visual inspection of Table 3 shows that the vowel identification scores were substantially higher than the consonant identification scores for both prelingually and postlingually deaf CI users and that the total vowel score was approximately 16% higher than the total consonant score. This can be explained by the known fact that vowels have more acoustic energy than most consonants. The vowels in the CVC test words also have longer duration than the consonants in the VCV test words and may therefore be easier to perceive, as the participants have more time to listen to them.

The consonant score for the prelingually deaf implant users was below 50% and more than 10% lower than the consonant score for the postlingually deaf (see Table 3). When we examined the six included studies with prelingually deaf participants, we noticed that they all had participants with a high age at implantation (range = 6.8–31.5 years) and, thus, long duration of deafness before implantation. Many studies have shown that prelingually deaf individuals younger than 2 years of age at implantation are more likely to obtain higher benefit from the implant for open speech perception than prelingually deaf implanted at a higher age (May-Mederake, 2012; Quittner, Cejas, Wang, Niparko, & Barker, 2016; Tobey et al., 2013). Studies conducted with prelingually deaf children implanted earlier than at 1 year of age show even that their speech perception measures are superior to the corresponding measures for postlingually deaf CI users, for prelingually deaf, later-implanted children, and for CI users with a progressive hearing loss before implantation (Colletti, Mandalà, & Colletti, 2012; Dettman et al., 2016; Holman et al., 2013).

Research Question 2: Vowels and Consonants Most Frequently Confused and Most Frequently, Correctly Identified

In 11 of the included articles in our meta-analysis, consonant confusions were presented in CMs, making

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Table 6. Confusion matrix of the three most frequently confused consonants pooled across 13 studies.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>/p/</th>
<th>/t/</th>
<th>/k/</th>
<th>/b/</th>
<th>/d/</th>
<th>/m/</th>
<th>/n/</th>
<th>/s/</th>
<th>/z/</th>
</tr>
</thead>
<tbody>
<tr>
<td>/p/</td>
<td>11.4</td>
<td>6.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
<td></td>
<td>18.9</td>
</tr>
<tr>
<td>/t/</td>
<td></td>
<td>7.5</td>
<td>10.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.6</td>
</tr>
<tr>
<td>/k/</td>
<td></td>
<td></td>
<td>3.7</td>
<td>18.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22.2</td>
</tr>
<tr>
<td>/b/</td>
<td></td>
<td></td>
<td></td>
<td>3.0</td>
<td>4.3</td>
<td></td>
<td></td>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>/d/</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>/m/</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.1</td>
<td></td>
<td></td>
<td>18.1</td>
</tr>
<tr>
<td>/n/</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.5</td>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>/s/</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>/z/</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
</tr>
</tbody>
</table>

Note. The three most frequently confused consonants in each confusion matrix were picked, assigned to an index equal to the number of participants in the study, added together with the results from the other matrices, and included in this table. The percentages in the table cells were calculated by dividing the number of confusions in each cell by the total number of confusions. The cell with the highest percentage shows the most frequent consonant confusion of the 13 studies.

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Table 7. Means, standard deviations, and ranges for the moderator variables for the prelingually and postlingually deaf CI users.

<table>
<thead>
<tr>
<th>Moderator variable</th>
<th>Postlingually deaf</th>
<th>Prelingually deaf</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (SD) (years)</td>
<td>N</td>
<td>Range (years)</td>
</tr>
<tr>
<td>Age at implantation</td>
<td>49.7 (18.3)</td>
<td>37</td>
<td>7.9–68.8</td>
</tr>
<tr>
<td>Duration of implant use</td>
<td>3.4 (1.6)</td>
<td>35</td>
<td>1.0–10.0</td>
</tr>
</tbody>
</table>

Note. CI = cochlear implant.
the results easy to quantify. In the spirit of meta-analytic approach, the CMs from the 11 articles were merged into one meta-CM displaying the three most frequently confused consonants from each CM.

It is a well-known phenomenon in phonetic and audiologic research that confusions between speech sounds most frequently happen within a group of sounds with different place of articulation but similar manner of articulation. Fant (1973) showed that the acoustic similarities of consonants grouped according to manner of articulation, for instance, stops, fricatives, and nasals, are significant for speech sound perception. The most frequently confused consonants in this study had the same manner of articulation and were thus acoustically similar and differed only in place of articulation. /t/ is an unvoiced dental/alveolar stop, and /k/ is an unvoiced velar stop. /m/ and /n/ are voiced nasals. In both confusions, different places of articulation were confused within the same category of manner of articulation.

The relatively high percentage of correct identification scores for the unvoiced stop consonants /t/ and /k/ in VCV context displayed in Table 5 can be explained by the fact that CI users listen to formant transitions in the adjacent vowels for identification. Consonants with the same manner but different place of articulation would be difficult to identify if formant transitions were not available. Moreover, the quality of the aspiration of the unvoiced stops also makes them easier to recognize than the voiced stops. There is a distinct audible difference between the aspiration following the pronunciation of /p/, /t/, and /k/, resembling the sound of the corresponding fricatives produced in the same place.

/t/ and /k/ were found to be the most frequently, correctly identified consonants, but /k/ was also the consonant most frequently confused, namely, with /t/. This may seem contradictory, but the explanation is most likely that the other consonants in the CMs of the included studies, /b, d, n, m, s, z/, are confused more broadly and more frequently with a number of other speech sounds, and also with those not included in our study, whereas the three unvoiced stops are almost exclusively confused among themselves. Apparently, CI users perceive the unvoiced stops as the most audibly distinct group among the consonants included in this study.

Research Question 3: The Association Between Age at Implantation, Duration of Implant Use, and Real-Word Monosyllable Score on Vowel and Consonant Identification Scores in Prelingually and Postlingually Deaf CI Users

Due to the low number of included studies reporting consonant or vowel identification score for the prelingually deaf, a statistical analysis of the associations with the moderators could not be performed for this group. However, many previous studies have investigated this, and it is well known that age at implantation plays an important role for the outcome of speech perception tests for prelingually deaf CI users (Holman et al., 2013; Tobey et al., 2013). Presumably, this is also the case for vowel and consonant tests measured by nonsense words.

For the postlingually deaf CI users, we constructed a univariate regression model in which duration of implant use could explain 59% of the variance in consonant score. After implantation, the CI users need a period of adaptation to the implant sound, which, in most cases, can vary from 3 months to 1 year. Thus, until stability of the fitting parameters is reached, the implantees will experience a gradual improvement of the benefit of the implants. Schmidt and Griesser (1997) showed that this stability was reached after about 1 year.

Earlier studies have shown that there is a close relationship between consonant and vowel identification scores and real-word monosyllable scores (e.g., Rødvik, 2008). Due to the low number of studies that reported real-word monosyllable scores in quiet for the postlingually deaf implantees (N = 14), we could not confirm this relationship in the meta-analysis. It also needs to be pointed out that, in the included studies, three different real-word monosyllable tests were used, and the consistency of the pooled means may therefore not be satisfactory.

Limitations

Exclusion of Studies Reporting Vowel Identification Scores Measured by Real Words

Our set criterion of only including studies which measured vowel and consonant scores by nonsense words demanded the exclusion of studies in which real words were used. The hVd nine-vowel test by Tyler et al. (1983) and the hVd 12-vowel test by Hillenbrand et al. (1995) were used to calculate vowel identification scores in 28 of the included studies, in which consonant identification scores were also measured. The test scores were excluded from this meta-analysis, as all of the hVd-combinations produced real English words, and also included diphthongs. Among the six included studies in which vowel scores were measured using nonsense words, three described Swiss participants (French-speaking; Cosendai & Pelizzone, 2001; Gani et al., 2007; Pelizzone et al., 1999), one described Japanese (Ito et al., 1994), and two described English-speaking participants from the United States (Kirk et al., 1992). It appears that many of the studies conducted with English-speaking participants use tests with real words in vowel identification testing, but tests with nonsense syllables in consonant identification testing. Studies conducted with participants with other native languages more often use nonsense syllables for obtaining vowel identification score as well. The reason might be lack of a validated nonsense syllable vowel test in English or that other languages do not have as many minimal pairs or triplets as the English language.

The consequences of excluding studies in which real words were used to measure consonant and vowel identification scores can be considered both positive and negative. On the positive side, consonant and vowel scores are collected from a homogenous material and can be compared
cross-linguistically. On the negative side, the collected material is smaller than it would have been if consonant and vowel scores measured by real words were included, and thus, the statistical power is lower.

**Use of Nonsense Syllable Tests to Avoid Ceiling Effects in Speech Perception Testing**

When the outcomes of speech perception tests approach the ceiling effect, the tests should be replaced with more difficult tests. This is usually done in two different ways, either by adding noise to test words and sentences or by exchanging the real-word tests with nonsense syllable tests. These are two very different approaches of increasing the levels of difficulty, and both have advantages and disadvantages. A speech-in-noise test is most frequently preferred in clinics, and one reason may be that such tests allow for the assessment of speech perception in everyday situations, which often involve a degree of environmental noise. Although the nonsense syllable identification test does not correspond closely to everyday speech perception situations, it has a major advantage in its relative independence of cognitive and contextual factors, such as language abilities, language experience, inferential skills, working memory capacity, and use of sentence context for comprehension. Such a test is valuable in research and in clinics, as it provides information about minute details of the speech sound perception of the implantees, details that cannot easily be obtained with other tests. This is useful for the fitting of implants and for the planning of individual listening therapy.

**Choice of Time Frame for the Inclusion of Articles**

The articles included in the meta-analysis range in publication year from 1989 to 2016 and report test results on CI users with multichannel implants of four channels or more. The validity of our choice is confirmed by Figure 5, which shows that the correlation between publication year and consonant score in the included articles is low and not statistically significant (.187; \( p = .202 \)). Hence, other factors than implant technology would probably explain the consonant score or dominate in a regression model with consonant score as the dependent variable.

Since 1989, there has been a transition from analog strategies in Symbion/Ineraid and feature extraction strategies in previous Cochlear devices (F0F2 and F0F1F2), to n-of-m and derivate of CIS stimulation strategies. More recently, there has been a transition to the fine structure stimulation strategies from Med-El. These strategies convey the fundamental frequency in the coding algorithm. All these modern strategies are spectral resolution strategies and, thus, can deliver pitch information to the inner ear, unlike the previous single-channel implants. The spectral resolution strategies are mainly pulsatile strategies, except for the analog strategies, and thus, the information is delivered to the electrodes using a set of narrow pulses in a nonsimultaneous fashion. Some of the recent stimulation strategies from Advanced Bionics even employed combined pulsatile and simultaneous (analog) stimulation strategies.

There has been a development in the microphone technology since the early years of CI. The input frequency range has increased, and the overall microphone quality has improved. However, the microphone sensitivity and the internal noise of the microphones have not improved noteworthy, although the availability of good microphones has increased. The benefit of increased frequency range in the speech processors for the postlingually deaf can also be discussed because the perceived pitch depends on where the implant is located in the cochlea rather than on the input frequency range of the microphone. Thus, the improvements in speech processor technology may not be of great importance in a clinical test situation with a good signal-to-noise ratio.

The largest improvements and developments of the implant technology since 1989 have followed the advances in conventional hearing aids by integrating a large amount of technology from the hearing aid industry. For instance, refined and further developed automatic gain controls with new noise reduction and compression algorithms have been implemented in the speech processors from all implant manufacturers. Also, there has been a trend toward smaller processors and toward controlling the speech processors by remote controls or by “apps” on the users’ smartphones. All this may have had substantial impact on the speech perception in daily life but probably only minor impact on speech perception in a clinical environment.

**Conclusions**

This systematic review and meta-analysis included peer-reviewed studies using nonsense syllables to measure the consonant and vowel identification scores of CI users, both with and without control groups.

The mean performance on consonant identification tasks for the postlingually deaf CI users from 44 studies
was higher than for the prelingually deaf users, reported in six studies. No statistically significant difference between the scores for prelingually and postlingually deaf CI users was found.

The consonants that were not correctly identified were typically confused with other consonants with the same acoustic properties, namely, voicing, duration, nasality, and silent gaps.

A univariate metaregression model with consonant score against duration of implant use for postlingually deaf adults indicated that duration of implant use predicts a substantial portion of their consonant identification ability. No statistical significance was found using this model.

Tests with monosyllabic and bisyllabic nonsense syllables have been employed in research studies on CI users’ speech perception for several decades. These kinds of studies expose information about the hearing of cochlear-implanted patients, which the standard test batteries in most audiology clinics do not reveal, information that is very useful for the mapping of CIs and for the planning of habilitation and rehabilitation therapy. Such tests may also give valuable information for further development of CI technology. We therefore propose that nonsense syllable tests be used as part of the standard test battery in audiology clinics when assessing the speech perception of CI users.

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References

Studies marked with an asterisk have been included in the meta-analysis.


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Appendix (p. 1 of 5)

Search Syntax

Database: EMBASE Classic + EMBASE <1947 to 2014 July 02>

1. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (164)
2. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (534)
3. 1 or 2 (693)
4. (nonsense word* or nonword* or pseudo word*).mp. (2167)
5. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. (475)
6. Cochlear Implants/ (9918)
7. Cochlear Implantation/ (64151)
8. [or/6–9,19,25] (0)
9. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (164)
10. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (534)
11. 9 or 10 (693)
12. (nonsense word* or nonword* or pseudo word*).mp. (2167)
13. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. (475)
14. Cochlear Implants/ (9918)
15. Cochlear Implantation/ (64151)
16. ((cochlear or auditive or auditory or hearing) adj2 (implant* or prosthes*)).mp. (11677)
17. “prostheses and orthoses”/ (12910)
18. sensory aid/ (40)
19. hearing aid/ (11172)
20. exp hearing disorder/th [Therapy] (6721)
21. exp hearing impairment/rh, th [Rehabilitation, Therapy] (7593)
22. (implant* or prosthes*).mp. (561843)
23. 17 or 18 or 19 or 20 or 21 or 22 (575414)
24. cochlea/ (17468)
25. cochlea*.mp. [mp = title, abstract, subject headings, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword] (49355)
26. 24 or 25 (49355)
27. 23 and 26 (13633)
28. (implant* or prosthes*).mp. (561843)
29. hearing aid/ (11172)
30. exp hearing impairment/rh, th [Rehabilitation, Therapy] (7593)
31. exp hearing disorder/th [Therapy] (6721)
32. 29 or 30 or 31 (18475)
33. 28 and 32 (4939)
34. or/14–17,27,33 (87916)
35. 11 or 12 or 13 (3261)
36. 34 and 35 (145)
Appendix (p. 2 of 5)

Search Syntax

Database: Ovid MEDLINE® In-Process & Other Non-Indexed Citations and Ovid MEDLINE® <1946 to Present>
1. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (117)
2. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (360)
3. 1 or 2 (473)
4. (nonsense word* or nonword* or pseudo word*).mp. (2020)
5. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. (389)
6. Cochlear Implants/ (6699)
7. Cochlear Implantation/ (3664)
8. 6 or 7 (8764)
9. ((cochlear or auditive or auditory or hearing) adj2 (implant* or prosthes*)).mp. (10940)
10. “Prostheses and Implants”/ (36221)
11. Sensory Aids/ (987)
12. Hearing Aids/ (6699)
13. exp Hearing Loss/rh, th [Rehabiliation, Therapy] (9705)
14. exp Persons With Hearing Impairments/rh [Rehabilitation] (488)
15. exp Hearing Disorders/th [Therapy] (5609)
16. (implant* or prosthes*).mp. (452036)
17. or/10–16 (462905)
18. cochlea*.mp. (39651)
19. Cochlea/ (15557)
20. 18 or 19 (39651)
21. 17 and 20 (11732)
22. (implant* or prosthes*).mp. (452036)
23. Hearing Aids/ (6699)
24. exp Hearing Loss/rh, th [Rehabilitation, Therapy] (9705)
25. exp Persons With Hearing Impairments/rh [Rehabilitation] (488)
26. exp Hearing Disorders/th [Therapy] (5609)
27. 23 or 24 or 25 or 26 (15328)
28. 22 and 27 (5255)
29. 23 or 24 or 25 or 26 (15328)
30. 22 and 27 (5255)
31. 29 and 30 (144)

Database: PsycINFO <1806 to June Week 4 2014>
1. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (168)
2. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (484)
3. 1 or 2 (648)
4. (nonsense word* or nonword* or pseudo word*).mp. (4252)
5. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. (1587)
6. exp Cochlear Implants/ (1620)
### Appendix (p. 3 of 5)

#### Search Syntax

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<td>exp Prostheses/ or &quot;prostheses and implants&quot;.mp.</td>
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<td>10.</td>
<td>(implant* or prosthese*).mp.</td>
<td>(12952)</td>
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<td>11.</td>
<td>8 or 9 or 10 (28173)</td>
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<td>12.</td>
<td>cochlea*.mp. or cochlea/ [mp = title, abstract, heading word, table of contents, key concepts, original title, tests &amp; measures]</td>
<td>(5518)</td>
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<td>13.</td>
<td>11 and 12 (2795)</td>
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<td>(implant* or prosthese*).mp.</td>
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<td>18.</td>
<td>14 and 17 (2009)</td>
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<td>19.</td>
<td>or/6–7,13,18 (2854)</td>
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<td>20.</td>
<td>3 or 4 or 5 (6354)</td>
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<td>21.</td>
<td>19 and 20 (56)</td>
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</table>

Database: ERIC <1965 to June 2014>

NB: Because of difficulties in adapting the search strategy in part b), we ran two searches; one adapted search with ERIC subject headings (18 hits) and the EMBASE search, which produced additionally five articles.

1. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (53)
2. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (109)
3. 1 or 2 (160)
4. (nonsense word* or nonword* or pseudo word*).mp. [mp = abstract, title, heading word, identifiers] (1107)
5. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. [mp = abstract, title, heading word, identifiers] (100)
6. Cochlear implants/ or Cochlear implantation/ (1846)
7. ((cochlear or auditive or auditory or hearing) adj2 (implant* or prosthese*)).mp. (499)
8. “prostheses and implants”/ or sensory aids/ or hearing aids/ or exp hearing loss/th, rh or hearing impaired persons/rh or hearing disorders/th or (implant* or prosthese*).mp. (2727)
9. Cochlea*.mp. or Cochlea/ (2065)
10. 8 and 9 (2032)
11. (implant* or prosthese*).mp. (706)
12. hearing aids/ or exp hearing loss/th, rh or hearing impaired persons/rh or hearing disorders/th (1846)
13. 11 and 12 (324)
14. or/6–7,10,13 (2035)
15. 3 or 4 or 5 (1349)
16. 14 and 15 (23)
17. (speech sound adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (53)
18. (phoneme adj2 (repetition or recognition or confusion or identification or discrimination or perception)).mp. (109)
19. 17 or 18 (160)
20. (nonsense word* or nonword* or pseudo word*).mp. (1107)
21. (nonword* syllable* or nonsense syllable* or pseudo syllable*).mp. (100)
Appendix (p. 4 of 5)

Search Syntax

22. "cochlear implant".mp. [mp = abstract, title, heading word, identifiers] (492)
23. ((cochlear or auditive or auditory or hearing) adj2 (implant* or prosthes*)).mp. (499)
24. (prostheses and implants).mp. [mp = abstract, title, heading word, identifiers] (0)
25. exp Sensory Aids/ (565)
26. hearing aids.mp. (332)
27. hearing impairments/ (6689)
28. exp Deafness/ (6685)
29. (implant* or prosthes*).mp. (706)
30. 25 or 26 or 27 or 28 or 29 (12097)
31. cochlea*.mp. [mp = abstract, title, heading word, identifiers] (530)
32. 30 and 31 (524)
33. (implant* or prosthes*).mp. (706)
34. hearing aids.mp. (332)
35. exp Hearing Impairments/ (11489)
36. 34 or 35 (11513)
37. 33 and 36 (449)
38. or/22–23,32,37 (532)
39. 19 or 20 or 21 (1349)
40. 38 and 39 (18)
41. 16 or 40 (23)
42. 41 not 40 (5)

Database: Web of Science/Web of Knowledge

1. TS = ("speech sound" NEAR/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))
2. TS = (phoneme NEAR/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))
3. TS = (consonant NEAR/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))
4. TS = (vowel NEAR/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))
5. TS = ("nonsense word" or "nonword" or "pseudo word")
6. TS = (« nonword syllable » or « nonsense syllable » or « pseudo syllable »)
7. #6 OR #5 OR #4 OR #3 OR #2 OR #1
8. TS = ("Cochlear implants" or "Cochlear implantation")
9. TS = ((cochlear or auditive or auditory or hearing) near/2 (implant* or prosthes*))
10. TS = ("prostheses and implants" or "sensory aids" or "hearing aids" or "hearing loss" or "hearing disorders" or (implant* or prosthes*)))
11. TS = (Cochlea*)
12. #11 AND #10
13. TS = (implant* or prosthes*)
14. TS = ("hearing aids" or "hearing loss" or "hearing disorders" or "hearing impair")
Appendix (p. 5 of 5)

Search Syntax

15.  #14 AND #13
16.  #15 OR #12 OR #9 OR #8
17.  #16 AND #7

Database: Scopus (Elsevier)
(TITLE-ABS-KEY("Cochlear implant*")) OR
(TITLE-ABS-KEY((cochlear or auditive or auditory or hearing) PRE/2 (implant* or prosthes*))) or ((TITLE-ABS-KEY("prostheses and implants" or "sensory aids" or "hearing aids" or "hearing loss" or "hearing impaired persons" or "hearing disorders" or (implant* or prosthes*))) and
(TITLE-ABS-KEY(cochlea*))) or
((TITLE-ABS-KEY(implant* or prosthes*)) and
(TITLE-ABS-KEY("hearing aids" or "hearing loss" or "hearing impaired persons" or "hearing disorders"))) and
((TITLE-ABS-KEY("speech sound" PRE/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score)) OR
TITLE-ABS-KEY(phoneme PRE/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score)) OR
TITLE-ABS-KEY(vowel PRE/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))) or
((TITLE-ABS-KEY("nonsense word*" or nonword* or "pseudo word*")) OR TITLE-ABS-KEY("nonword* syllable*" or "nonsense syllable*" or "pseudo syllable*")) or (((TITLE-ABS-KEY("speech sound" PRE/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score)) OR TITLE-ABS-KEY(phoneme PRE/2 (repetition or recognition or confusion or identification or discrimination or perception or test or score))) OR TITLE-ABS-KEY("nonsense word*" or nonword* or "pseudo word*")) OR TITLE-ABS-KEY("nonword* syllable*" or "nonsense syllable*" or "pseudo syllable*")))

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