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Consonant and vowel identification in cochlear implant users measured by nonsense words:

A systematic review and meta-analysis

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1 **Abstract**

2 **Purpose**

3 The purpose of this systematic review and meta-analysis was to establish a baseline of
4 the vowel and consonant identification scores in pre- and postlingually deaf users of multi-
5 channel cochlear implants (CIs) tested with CVC (consonant-vowel-consonant) and VCV
6 (vowel-consonant-vowel) nonsense syllables.

7 **Method**

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

13 **Results**

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

22 **Conclusions**

23 The mean performance on consonant identification tasks for the pre- and postlingually
24 deaf CI users was found. There were no statistically significant differences between the scores
25 for pre- and postlingually deaf CI users. The consonants that were incorrectly identified, were

1 typically confused with other consonants with the same acoustic properties; namely voicing,
2 duration, nasality, and silent gaps. A univariate meta-regression model, although not
3 statistically significant, indicated that duration of implant use in postlingually deaf adults
4 predict a substantial portion of their consonant identification ability.

5 As there is no ceiling effect, a nonsense syllable identification test may be a useful
6 addition to the standard test battery in audiology clinics when assessing the speech perception
7 of CI users.

8

9 Keywords: Speech perception, Consonants, Vowels, Cochlear Implants, Hearing, Audiology

1 **Introduction**

2 The offering of multi-channel cochlear implants (CIs) to profoundly deaf and hard-of-
3 hearing adults and children is a well-established medical procedure today, and there are more
4 than 600,000 CI users in the world (The Ear Foundation, 2016). The CI is offered to patients
5 with a large variety of causes for their hearing loss, and leads to a considerable improvement
6 in hearing for the majority of users. There is, however, large variability in speech perception
7 outcomes after cochlear implantation (Dowell, Dettman, Blamey, Barker, & Clark, 2002;
8 Rotteveel et al., 2010; Välimaa & Sorri, 2000). Thus, it is critical to have precise measures of
9 how well CI users can perceive different speech sounds. Such measures are important for the
10 fitting of CIs and testing of new implant technology, but also for planning and assessing the
11 effects of listening training and speech therapy. In recent years, traditional speech perception
12 tests using sentences and words as stimuli have increasingly produced ceiling or near-ceiling
13 effects in CI users (Blamey et al., 2013). This may be due to a number of factors such as
14 shorter time of deafness before implantation, increased residual hearing of the implant
15 candidates, and better hearing preservation in CI surgery. There is therefore an increasing
16 need for more difficult tests which provide fine-grained information on perception of
17 consonants and vowels. Speech perception tests with nonsense words, which are more
18 difficult than real word tests and less reliant on prior experience with a specific language,
19 appear to be a valuable alternative for future clinical practice and research. However, in order
20 for nonsense word tests to be maximally useful, it is necessary to establish a baseline of the
21 typical level of consonant and vowel perception that CI users achieve on these tests.
22 Additionally, it is important to determine how this baseline relates to performance on other
23 speech perception tests for both pre- and postlingually deaf CI users. The present systematic
24 review and meta-analysis investigates the typical performance of CI users in nonsense word

1 tests, as well as the influence of some clinically relevant background factors on performance
2 in these tests.

3 **Testing of speech perception in CI users**

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

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

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

21 A common monosyllabic test is the consonant-vowel nucleus-consonant (CNC) test
22 created by Peterson and Lehiste (1962). This test is a special case of the CVC test, which both
23 tests the perception of real words and of speech sounds. The CNC word lists are a set of 10
24 lists of 50 phonemically balanced words. The test has been controlled for text-based lexical
25 frequency across lists. The Northwestern university auditory test no. 6 (NU-6) monosyllable

1 test is another test of word and speech sound recognition with monosyllables in the CVC-
2 format, consisting of 50 words and 150 speech sounds (Tillman & Carhart, 1966). Yet another
3 commonly used test is the Phonetically Balanced Kindergarten word test (PBK) (Haskins,
4 1949). The test contains four 50-word-lists, and is still extensively used for assessing speech
5 perception of hearing-impaired children. All these three tests are commonly used in English-
6 speaking countries, and have been adapted to many other languages.

7 Real-word monosyllable recognition scores have been shown to have a high
8 correlation with audiometric thresholds. In a study by Dubno, Lee, Klein, Matthews, and Lam
9 (1995), a confidence limit for maximum word recognition scores of the NU-6 was obtained
10 from 407 ears in a large group of young and aged subjects with confirmed cochlear hearing
11 losses. The relationship between the pure tone averages and the maximum word recognition
12 scores based on this study is displayed in a table in Stach (2009, p. 296).

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

23 **Open- or closed-set tests**

24 Speech perception is usually measured in either open- or closed-set/forced-choice test
25 conditions, depending on what kind of information the clinician is seeking. Open-set tests

1 provide a collection of detailed information about speech perception, listening capacity, and
2 acoustic properties, but require a substantial effort from the test leader for post-test analysis.
3 Open-set tests have relatively small learning effects for the patient, and can therefore be
4 performed reliably at desirable intervals.

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

11 Tests of mono- and bisyllabic words and sentences have traditionally been performed
12 in open-set conditions, while vowel and consonant identification tests have been performed in
13 closed-set conditions. Some commonly used closed-set tests of consonant and vowel
14 identification are those by Hillenbrand, Getty, Clark, and Wheeler (1995); Shannon, Jensvold,
15 Padilla, Robert, and Wang (1999); Tyler, Preece, and Tye Murray (1987); Van Tasell,
16 Greenfield, Logemann, and Nelson (1992). An open-set test of phoneme recognition and
17 confusion in Finnish is described by Välimaa, Määttä, Löppönen, and Sorri (2002a, 2002b).

18 **Consonant and vowel identification**

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

23 Vowels are characterized by the tongue position in the mouth cavity, and by the lip-
24 rounding. Tongue position can be high, low, back, or front. Normally, vowels are voiced, and
25 the air stream passes frictionless along the middle of the mouth cavity while the tongue is in a

1 static position. The vowel is the nucleus of a syllable, and a syllable can be one vowel alone
2 or a vowel with surrounding consonants. Consonants carry more varied types of phonetic
3 information than vowels, but many of them have lower duration and less acoustic energy.
4 Because of this, vowel sounds are often easier to perceive than consonants, and it is widely
5 accepted that vowels carry most of the intelligibility information in sentences (e.g. Kewley-
6 Port, Burkle, & Lee, 2007).

7 Previous research has confirmed that CI users have more difficulties identifying
8 consonants and vowels than persons with normal hearing, who typically achieve a score of
9 95-100% on consonant and vowel identification tests (Kirk, Tye-Murray, & Hurtig, 1992;
10 Sagi, Kaiser, Meyer, & Svirsky, 2009). In addition, consonant identification scores have
11 usually been measured to be lower than vowel scores. For instance, in two Finnish studies of
12 CI users, it was shown that 24 months after switch-on of the CIs the average vowel
13 recognition score was 80% and the average consonant recognition score was 71% (Välilmaa et
14 al., 2002a, 2002b).

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

21 Consonant and vowel identification tests provide more detailed information about the
22 hearing of CI users than word or sentence tests. Identification of consonants and vowels can
23 be measured both with real word or nonsense syllable identification tests, and the scoring can
24 be done by counting the number of correctly identified speech sounds. Other commonly used
25 consonant and vowel identification tests have vowel-consonant-vowel (VCV) or consonant-

1 vowel (CV) nonsense syllables as stimuli, and the consonants are typically presented in an [ɑ,
2 i], or [u] context with the target consonant in medial or initial position.

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

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

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

1 **Consonant and vowel confusions**

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

10 In vowel and consonant recognition studies of postlingually deaf adult CI users, some
11 predominant confusions have been identified. Van Wieringen and Wouters (1999) tested
12 vowel and consonant recognition in Flemish-speaking CI users and found that /y/ was often
13 confused with /e/, and /ɪ/ often confused with /ə/, showing that vowel length was recognized
14 correctly. The consonant, /t/ was often confused with /k/, and /ʁ/ was often confused with /z/,
15 indicating that voicing and manner of articulation were recognized correctly. Munson et al.
16 (2003) found that English-speaking CI users often confused /ɛ/ with /ɪ/ and /ɪ/ with /ε/,
17 concluding that they recognized vowel length. Moreover, /d/ was confused with /g/ and /θ/
18 with /f/, concluding that they recognized voicing and manner of articulation. Välimaa et al.
19 (2011) presented longitudinal data of vowel recognition and confusion patterns in Finnish
20 informants from before CI surgery until four years post implantation. They also studied the
21 effect of duration of profound hearing impairment before implantation, and the effect of the
22 use of different implant devices after implantation. After four years, the most frequent
23 confusions were /ø/ perceived as /æ/, and /e/ perceived as /ø/ or /æ/, which led to the
24 conclusion that the Finnish front vowels were the most difficult to distinguish. This is in
25 agreement with previous studies showing that vowels with smaller spectral differences are

1 often the most difficult to identify (Munson et al., 2003; Skinner, Fourakis, Holden, Holden,
2 & Demorest, 1996; Van Wieringen & Wouters, 1999).

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

8 **Nonsense syllable test words**

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

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

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

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

4 Nonsense words used in studies of speech perception usually contain only one, or at
5 most, two syllables, to avoid the influence of possibly poor phonological working memory
6 span on performance. However, some studies have used tests such as the Children's Nonword
7 Repetition test (Gathercole, Willis, Baddeley, & Emslie, 1994) and other nonsense word tests
8 primarily constructed to assess children's working memory span and cognitive abilities, to
9 study speech perception (Burkholder-Juhasz, Levi, Dillon, & Pisoni, 2007; Casserly & Pisoni,
10 2013; Nakeva Von Mentzer et al., 2015). The nonsense word test battery of Gathercole et al.
11 (1994) contains nonsense words with two, three, four, and five syllables, but even the
12 bisyllabic nonsense words are poorly suited to measure vowel and consonant identification, as
13 the same vowel or consonant can be found several times in the same word in different
14 positions and several times in the same test sequence. This makes it more complicated to
15 measure the prevalence of consonant or vowel confusions.

16 **Milestones in the development of cochlear implant technology**

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

1 The stimulation strategies of the early multi-channel implants were either analog or
2 pulsatile. The main difference between the two groups of strategies is that the first employ
3 simultaneous stimulation, while the latter employ sequential stimulation. A major
4 disadvantage with the analog stimulation strategy is channel interaction, an effect that
5 obstructs speech perception by sound distortion. This problem is less prevalent in pulsatile,
6 non-simultaneous stimulation. All the stimulation strategies currently used are pulsatile.

7 The discontinued implants from Ineraid/Symbion and from UCSF/Storz, employed the
8 compressed-analog (CA) stimulation strategy. The CA strategy was also employed by
9 Advanced bionics in their previous implants. Some years later Advanced bionics released
10 SAS (simultaneous analog stimulation), which is a modified CA strategy. This strategy was
11 applied until the mid-2000s. Several clinical studies have demonstrated open speech
12 understanding with analog stimulation strategies (e.g. Dorman, Hannley, Dankowski, Smith,
13 & McCandless, 1989), and several studies have also compared implants running pulsatile and
14 analog stimulation (Tyler et al., 1996; Tyler, Lowder, Parkinson, Woodworth, & Gantz, 1995;
15 Xu, Zwolan, Thompson, & Pfungst, 2005). The results have pointed towards better speech
16 perception with pulsatile stimulation than with analog, although there has been large
17 variability in the outcomes. Analog strategies are not used in CI processors today.

18 **Variables influencing speech perception in CI users**

19 It has been shown in many studies that there is a large variability in speech recognition
20 performance of CI users (Dowell et al., 2002; Rotteveel et al., 2010; Välimaa & Sorri, 2000).
21 For a given type of implant, auditory performance may vary from zero to 100% correct, and
22 thus the individual differences between CI users appear to be vastly larger than the effect of
23 implant manufacturer. Auditory performance is here understood as the ability to discriminate,
24 detect, identify, or recognize speech. A typical measure of auditory performance is the
25 percentage correct score on open-set speech recognition tests. The review article by Loizou

1 (1999) lists the following factors that have been found to affect auditory performance: The
2 duration of deafness prior to implantation (a long duration appears to have a negative effect
3 on auditory performance), age of onset of deafness (younger age is associated with better
4 outcome), age at implantation (earlier implantation is associated with better outcome for
5 prelingually deaf subjects), and duration of CI use (longer duration of CI experience is
6 associated with better outcome). Other factors that may affect auditory performance include
7 etiology of hearing loss, number of surviving spiral ganglion cells, electrode placement and
8 insertion depth, electrical dynamic range of the CI, cognitive abilities, duration of hearing aid
9 use before implantation, and signal processing strategy (Blamey et al., 2013; Blamey et al.,
10 2015; Rotteveel et al., 2010; Spencer, 2004; Wie, Falkenberg, Tvette, & Tomblin, 2007).

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

15 Some studies have even found that age at implantation is not a significant predictor of
16 speech perception outcome for prelingually deaf children (e.g. Geers, Brenner, & Davidson,
17 2003; Wie et al., 2007). Wie et al. (2007) found that the variations in performance on speech
18 perception tasks could be explained by daily user time, nonverbal intelligence, duration of CI
19 use, educational placement, and communication mode (use of sign language or spoken
20 language). The authors explained this result by the relatively high age at implantation for the
21 participants in the study, as only one participating child was implanted before 24 months of
22 age.

23 For a group of 65 postlingually implanted adults Plant, McDermott, van Hoesel,
24 Dawson, and Cowan (2016) showed different factors which predicted word recognition scores
25 for unilaterally and bilaterally implanted CI users. For the unilaterally implanted group

1 predictors included a shorter duration of severe to profound hearing loss in the implanted ear
2 and poorer pure-tone-averaged thresholds in the contralateral ear. For the bilateral group
3 shorter duration of severe to profound hearing loss before implantation, lower age at
4 implantation, and better contralateral hearing thresholds were associated with higher bilateral
5 word recognition in quiet and speech reception threshold (SRT) in noise.

6 **Transmission of consonants and vowels in an implant**

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

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

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

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

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

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

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

1 Details of the systematic review protocol were registered with PROSPERO, the
2 International prospective register of systematic reviews, on December 15, 2014. The protocol
3 is available online at:

4 http://www.crd.york.ac.uk/prospero/display_record.asp?ID=CRD42014015141.

5 The systematic review was performed in the following steps:

- 6 • Literature search
- 7 • Screening of articles for inclusion and exclusion
- 8 • Extraction of information from the articles (coding)
- 9 • Pooling of data for statistical analysis

10 A flow diagram displaying the process from searching, via screening and eligibility to
11 the final number of included articles, is shown in Figure 1. The diagram is based on a
12 template designed by PRISMA (Moher et al., 2009).

13 The forest plots displayed in Figures 2, 3 and 4 were generated by means of the
14 software CMA (Comprehensive Meta-analysis) (Borenstein, Hedges, Higgins, & Rothstein,
15 2014).

16 **Literature Searches**

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

22 The searches were run three times: On August 13, 2014, April 6, 2015, and October 9,
23 2016, and were limited to peer-reviewed journal articles written in English, in Scandinavian
24 languages (Norwegian, Swedish and Danish), and in Finnish. The search strings consisted of
25 two elements; a) various terms referring to nonsense words and speech discrimination and b)

1 terms referring to cochlear implants. All the search elements were truncated in order for the
2 searches to include all conjugations of the nouns. Truncation was represented by an asterisk
3 (*).

4 a) Nonsense word repetition with the synonyms nonword*, NW*, nonsense word*,
5 pseudo word*, nonsense syllable*, nonword syllable*, pseudo syllable*, CV* word*,
6 VC* word*, speech sound repetition*, speech sound recognition*, speech sound
7 confusion*, speech sound identification*, speech sound discrimination*, speech sound
8 perception*, phoneme repetition*, phoneme recognition*, phoneme confusion*,
9 phoneme identification*, and phoneme discrimination*.

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

12 Since “cochlear implant” is an unambiguous concept, unlike “nonsense word
13 repetition”, the number of search terms in b) turned out to be considerably lower than in a).
14 The complete search syntaxes for the four Ovid databases EMBASE, MEDLINE, PsycINFO,
15 and ERIC, as well as for Web of science and Scopus, are listed in Appendix 1.

16 **Screening of abstracts and review of full-text articles**

17 The search results were imported into EndNote, v. X7.7.1 (Thompson Reuters, 2016)
18 for removal of duplicates, books and book-chapters, dissertations, editorials, systematic
19 reviews, and articles in other languages than Danish, English, Finnish, Norwegian and
20 Swedish. Thereafter, the references were imported into the web-based systematic review
21 software DistillerSR (EvidencePartners, Ottawa, Canada), which was used for the screening
22 process.

23 Assessment of articles was performed in two phases: a) Screening of abstracts and
24 titles, and b) Full-text review of the remaining articles, as described in Figure 1. In phase a)
25 two researchers (the first author, AKR, and the fourth author, MAS) independently evaluated

1 all the identified titles and abstracts, and excluded the studies missing one or both of the
2 search terms “cochlear implants” and “nonsense words” with synonyms. Disagreements were
3 solved by discussion or by reading of the full text of the articles. Further on, the abstracts
4 were screened by AKR for number of participants, and studies with less than three
5 participants were excluded, as case-studies with one or two participants did not fit into the
6 methodology of the systematic review.

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

11 **Inclusion criteria**

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

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

22 **Exclusion criteria**

- 23 • Studies on participants with single-channel CIs were excluded. This was based on
24 research showing that implants need at least four channels to provide adequate speech
25 perception in quiet (Cohen, Waltzman, & Fisher, 1993; Tyler et al., 1988).

- 1 • Studies measuring consonant- or vowel score by real-word stimuli and not by
2 nonsense syllables were excluded.
- 3 • Studies measuring consonant- or vowel score by nonsense words with three or more
4 syllables were excluded, as it is difficult to disentangle effects of working memory
5 span from hearing when interpreting these results. In addition, the same target
6 consonants or vowels are often presented more than once in such multi-syllable test-
7 words.
- 8 • Studies assessing the identification of less than about 50% of the national inventory of
9 vowels and consonants were excluded, as these studies presented vowel and consonant
10 identification scores based on too few consonants and vowels to represent the
11 phoneme inventory of this language. For instance, there are 20-24 consonants in
12 English, depending on the dialect, and for the study to be included, at least half of
13 these had to be used to calculate a consonant identification score.
- 14 • Studies in which means and standard deviations of the consonant and vowel
15 identification score were not reported, only reported graphically in diagrams, or could
16 not be calculated from confidence intervals or standard errors, were excluded. For
17 those excluded studies published less than 10 years ago, we wrote to the
18 corresponding author to ask for the raw data from the study. Studies from which the
19 raw data were received were included in the meta-analysis.
- 20 • Studies in which nonsense words were presented live instead of recorded, were
21 excluded because of less expected consistency in the test results than in recorded
22 materials (Mendel & Owen, 2011).
- 23 • Studies in which the stimuli were presented with lip reading support were excluded.
- 24 • Studies using synthesized or electronically generated test stimuli were excluded.

- 1 • Studies displaying speech sound scores not separated into a vowel and a consonant
2 score were excluded.
- 3 • Studies in which the identification score for consonants was only reported as
4 categories according to consonant properties like place, manner or voicing (e.g.
5 Nelson, Van Tasell, Schroder, Soli, & Levine, 1995) were excluded.
- 6 • In those cases where different articles were based on the same study participants
7 and/or the same data, all but one of these articles were excluded. The article that
8 included the highest number of participants was selected for further analysis.
- 9 • Studies including participants with a contralateral hearing aid in addition to an implant
10 were excluded unless it was clearly stated in the article that the benefit of the implant
11 was better than the benefit of the hearing aid.

12 **Risk of publication bias**

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

1 **Quality assessment**

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

- 4 • inconsistent presentation of results
- 5 • errors in the analyses
- 6 • lack of transparency, e.g. missing description of the study methods

7 **Selection and coding of data**

8 A pilot coding was performed on 11 articles by MAS, to test the strength of the
9 categories in the coding form. After this, an evaluation of the pilot coding was performed by
10 the review team to develop the final coding form, in which the selection of coding parameters
11 was done based on our research questions. The following data were extracted from the articles:
12 Author, title of article, publication year, journal, aim, language, and study design, absence or
13 presence of a control group. For studies including participants with an implant the following
14 measures were coded: Number of participants, number of post-/ prelingually implanted
15 participants), number of participants with Auditory Neuropathy Spectrum Disorder (ANSD),
16 implant type, speech processing strategy, age at testing, age at implantation, duration of
17 implant use, duration of deafness before implantation, age at onset of deafness, stimulation
18 level, number of uni-, or bilaterally, sequentially, or bimodally implanted participants,
19 identification score for vowels, most confused vowel, identification score for consonants,
20 most confused consonant, monosyllable real word identification score, and score from post-
21 operative audiometric measurements. For normal-hearing participants serving as control
22 groups, the following measures were coded: Number of participants, identification score for
23 vowels, most confused vowel, identification score for consonants, most confused consonant,
24 and monosyllable real word identification score. The data were extracted to the form by AKR.

1 **Strategy for data synthesis**

2 Both aggregate and individual participant data were used. We used quantitative
3 methodology on the included studies which were sufficiently homogeneous. Vowel and
4 consonant identification scores and vowel and consonant confusions were compared between
5 studies as well as between languages, despite cross-linguistic differences (Tyler & Moore,
6 1992).

7 **Analysis**

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

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

18 To answer Research question 2, "Which consonants and vowels are most frequently
19 confused by CI users, and which consonants and vowels are most frequently identified
20 correctly?" we constructed meta confusion matrices to display the three most common vowel
21 and consonant confusions, from the 11 studies in which this information was available. In
22 some articles this information was given qualitatively, and in these cases our presentation of
23 the results was also given qualitatively.

24 To answer Research question 3, only users with postlingual deafness were included in
25 the analysis, as very few studies reported consonant and vowel scores for the prelingually deaf

1 group. We performed a univariate regression analysis with the weighted mean consonant
2 identification score against duration of CI use. Real word monosyllable score and vowel
3 identification score were omitted as independent and dependent variables in the analyses
4 because this was only reported in 17 studies and 6 studies, respectively. We obtained beta
5 regression coefficients to characterize the univariate relationship, and explained the
6 percentage of between-study variance by using R^2 , which quantifies the proportion of
7 variance explained by the covariates (Borenstein et al., 2009).

8 **Results**

9 **Study characteristics**

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

23 Six hundred thirteen participants were unilaterally implanted, 10 bilaterally and 24
24 bimodally. The number of participants per study varied between three and 56. Three articles
25 described CI users with a hearing aid on the contralateral ear (bimodal users) (Gani, Valentini,

1 Sigrist, Kos, & Boex, 2007; Incerti, Ching, & Hill, 2011; Sheffield & Zeng, 2012). From
2 these articles we included in our meta-analysis only the results obtained without a hearing aid.
3 In one of the articles, the participants' vowel perception was tested both with wVb- and with
4 bVb-words (Kirk et al., 1992). According to our inclusion criteria stating that the participants
5 should not be represented in the material more than once, we chose to use the bVb-words in
6 our analyses, as these gave the highest mean score of vowel perception.

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

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

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

1 **Research question 1: What are the typical vowel and consonant identification scores in**
2 **cochlear implant users when measured by nonsense syllables, and how do the typical**
3 **vowel and consonant identification scores differ in pre- and postlingually deaf**
4 **implantees?**

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

18 Consonant identification scores were reported in 46 articles (48 studies). Four of these
19 articles had to be excluded because the consonant scores could not be split into one score for
20 the prelingually deaf and one for the postlingually deaf (Kirk et al., 1992; Munson et al.,
21 2003; Stacey et al., 2010; Van Wieringen & Wouters, 1999). Consonant identification scores
22 were not reported for any of the normal-hearing control groups, which were included in 13 of
23 the studies. In many of these studies the control group was used for calibrating the consonant
24 and vowel identification test in the local dialect. This was done by requiring a score of 95% or
25 higher on the test by the control group, before the test could be used for testing cochlear

1 implanted participants. If the score for the control group turned out to be lower than the limit
2 set in the study, the consonant identification test was modified to get the score above the limit,
3 for instance by removing nonsense syllables with high failure rates from the test, e.g. certain
4 test words pronounced in a dialect little known to the participants.

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

9 Only five studies reported consonant identification scores for both the pre- and
10 postlingually deaf CI users, and no studies reported vowel identification scores for both
11 groups. Consonant identification scores for the postlingually deaf users were on average 10.9%
12 better than for the prelingually deaf users ($SD = 39.7\%$, range: $-22.5\text{--}47.5\%$, $z[5] = 0.61$).
13 This difference in scores was not statistically significant ($p = 0.54$, $df = 4$). Hence, it is
14 unclear whether there is a difference in consonant perception between prelingually and
15 postlingually deaf CI users.

16 **Research question 2: Which consonants and vowels are most frequently confused by CI**
17 **users, and which consonants and vowels are most frequently identified correctly?**

18 **Vowel confusions**

19 Details on individual vowel confusions were reported in only one of the included
20 articles (containing two studies) (Kirk et al., 1992), but were based on quantitative data from
21 27 confusion matrices (CMs). This article reports results from normal-hearing participants
22 from and two groups of CI users; Ineraid and Nucleus-users. Vowel stimuli were given both
23 in bVb-context and in wVb-context. Identifications and misidentifications were reported
24 qualitatively, and for the normal-hearing subjects only a few errors were made. In the bVb-
25 context mean vowel identification was 50.5% ($SD = 4.8\%$, range: $30.0\text{--}77.7\%$) for Cochlear

1 CI users and 52.0% ($SD = 4.0\%$, range: 32.5–82.5%), for Ineraid CI users. In the wVb-context
2 the vowel identification scores were somewhat lower than in the bVb-context for both
3 implants. In summary, the long vowels /i:/, /æ:/, /ɑ:/, and /u:/, were seldom misidentified, but the
4 short vowels /ɪ, ε, ʌ/, and /ʊ/ were often confused with other short vowels. /ʊ/, was sometimes,
5 however, also confused with /ɑ:/ in wVb-context. Additionally, a higher number of short
6 vowels were confused in the wVb-context than in the bVb-context.

7 **Consonant confusions**

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

22 In two studies (Dorman et al., 1990; Munson et al., 2003), the participants were
23 divided into poor and better performers, in one study the participants were divided into poor,
24 intermediate and better performers (Van Wieringen & Wouters, 1999), and in two studies the
25 participants were divided into three groups according to type of implant (Doyle et al., 1995)

1 or according to native language of participants (Tyler & Moore, 1992). In each of these
2 studies, the data from the CM of each group was plotted into the table and the meta-CM. Thus,
3 a total of 17 CMs were pooled into Table 5 and the meta-CM in Table 6.

4 In three of the articles several consonant identification tests were given to the same
5 participants. We chose the better of the two outcomes when two speech processors were
6 compared (Dorman & Loizou, 1996; McKay et al., 1992). We chose the outcomes based on
7 use of CI alone if one CM was made based on the CI alone and one on CI + hearing aid
8 (Incerti et al., 2011). In one article (Donaldson & Kreft, 2006) the consonant identification
9 tests were performed in six contexts; Ca, Ci, Cu, aCa, iCi, and uCu, and averaged over all
10 conditions. We included the pooled data in our analyses. When several CMs were presented,
11 obtained with and without background noise and with and without lip reading (Incerti et al.,
12 2011), testing in quiet and auditory only condition was chosen.

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

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

17 **Research question 3: a) To what extent are age at implantation, duration of implant use,**
18 **and real word monosyllable score associated with variations in consonant and vowel**
19 **identification performance in nonsense syllable tasks for prelingually deaf CI users?**
20 **b) To what extent are duration of implant use, and real word monosyllable score**
21 **associated with variations in consonant and vowel identification performance in**
22 **nonsense syllable tasks for postlingually deaf CI users?**

23 a)

24 The weighted scores of age at implantation, duration of implant use for the pre- and
25 postlingually deaf CI users are reported in Table 7. The monosyllable scores are reported in

1 Table 3. Since only six studies report results for prelingually deaf CI users, a bivariate meta-
2 regression was not carried out, and Research question 3 a) could not be answered.

3 b)

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

8 We decided to omit monosyllable scores from the multiple regression model with
9 postlingually deaf CI users due to a small number of studies ($N = 13$). A univariate regression
10 model was then constructed with the moderator variable duration of implant use and the
11 independent variable consonant identification score. The results of the univariate regression
12 were $\beta = 2.6$, $S.E. = 1.4$, 95% conf. int. $[-0.22, 5.3]$, $z[36] = 1.81$, and not significant ($p =$
13 0.071). The proportion of total between-study variance explained by the model was $R^2 = 0.59$,
14 $N = 36$.

15 **Publication bias**

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

23 By visual inspection of the funnel plot for the consonant identification scores of the
24 postlingually deaf, we noticed that the studies were slightly scattered to the left of the mean of

1 the funnel plot. The asymmetry in the funnel plot may be a sign of publication bias,
2 heterogeneity, or chance.

3 **Discussion**

4 The purpose of this systematic review and meta-analysis is to establish a baseline of
5 the vowel and consonant identification scores in pre- and postlingually deaf users of multi-
6 channel cochlear implants (CIs) tested with CVC (consonant-vowel-consonant) and VCV
7 (vowel-consonant-vowel) nonsense syllables.

8 The mean consonant and vowel identification scores for the pre- and postlingually
9 deaf CI users show that performance was well below ceiling for both groups, and that there
10 were higher scores for vowels than for consonants. The mean differences between the
11 consonant identification scores for the pre- and postlingually deaf CI users were not
12 statistically significant.

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

17 In a univariate regression model between duration of implant use and consonant
18 identification score for postlingually deaf CI users, duration of implant use explained 59% of
19 the variance in effect sizes. The model was not statistically significant ($p = 0.071$).

20 **Research question 1: Typical vowel and consonant identification scores**

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

1 score of prelingually deaf CI users and five articles reported vowels scores of postlingually
2 deaf CI users.

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

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

1 **Research question 2: Vowels and consonants most frequently confused and most**
2 **frequently correctly identified.**

3 In 11 of the included articles in our meta-analysis consonant confusions were
4 presented in confusion matrices (CMs), making the results easy to quantify. In the spirit of
5 meta-analytic approach, the CMs from the 11 articles were merged into one meta-CM
6 displaying the three most frequently confused consonants from each CM.

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

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

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

9 **Research question 3: The association between age at implantation, duration of implant**
10 **use, and real word monosyllable score on vowel and consonant identification scores in**
11 **pre- and postlingually deaf CI users.**

12 Due to the low number of included studies reporting consonant or vowel identification
13 score for the prelingually deaf, a statistical analysis of the associations with the moderators
14 could not be performed for this group. However, many previous studies have investigated this,
15 and it is well known that age at implantation plays an important role for the outcome of
16 speech perception tests for prelingually deaf CI users (Holman et al., 2013; Tobey et al.,
17 2013). Presumably, this is also the case for vowel and consonant tests measured by nonsense
18 words.

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

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

8 **Limitations**

9 **Exclusion of studies reporting vowel identification scores measured by real words**

10 Our set criterion of only including studies which measured vowel and consonant
11 scores by nonsense words, demanded the exclusion of studies in which real words were used.
12 The hVd nine-vowel test by Tyler et al. (1983) and the hVd 12-vowel test by Hillenbrand et al.
13 (1995) were used to calculate vowel identification scores in 28 of the included studies, in
14 which consonant identification scores were also measured. The test scores were excluded
15 from this meta-analysis, as all of the hVd-combinations produced real English words, and also
16 included diphthongs. Among the six included studies in which vowel scores were measured
17 using nonsense words, three described Swiss participants (French-speaking) (Cosendai &
18 Pelizzone, 2001; Gani et al., 2007; Pelizzone et al., 1999), one described Japanese (Ito et al.,
19 1994) and two described English-speaking participants from the U.S. (Kirk et al., 1992). It
20 appears that many of the studies conducted in English-speaking countries use tests with real
21 words in vowel identification testing, but tests with nonsense syllables in consonant
22 identification testing. Studies conducted in the countries with the other native languages we
23 have studied, more often use nonsense syllables for obtaining vowel identification score as
24 well. The reason might be lack of a validated nonsense syllable vowel test in English or that
25 other languages do not have as many minimal pairs or triplets as the English language.

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

7 **Use of nonsense syllable tests to avoid ceiling effects in speech perception testing**

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

23 **Choice of time-frame for the inclusion of articles**

24 The articles included in the meta-analysis range in publication year from 1989 until
25 2016, and report test results on CI users with multi-channel implants of four channels or more.

1 The validity of our choice is confirmed by Figure 5, which shows that the correlation between
2 publication year and consonant score in the included articles is low and not statistically
3 significant (0.187; $p = 0.202$). Hence, other factors than implant technology would probably
4 explain the consonant score, or dominate in a regression model with consonant score as the
5 dependent variable.

6 Since 1989, there has been a transition from analog strategies in Symbion/Ineraid and
7 feature extraction strategies in previous Cochlear devices (F0F2 and F0F1F2), to n-of-m and
8 derivate of CIS stimulation strategies. More recently, there has been a transition to the Fine
9 Structure (FS) stimulation strategies from Med-El. These strategies convey the fundamental
10 frequency in the coding algorithm. All these modern strategies are spectral resolution
11 strategies, and thus can deliver pitch information to the inner ear, unlike the previous single-
12 channel implants. The spectral resolution strategies are mainly pulsatile strategies, except for
13 the analog strategies, and thus the information is delivered to the electrodes using a set of
14 narrow pulses in a non-simultaneous fashion. Some of the recent stimulation strategies from
15 Advanced bionics even employed combined pulsatile and simultaneous (analog) stimulation
16 strategies (SAS).

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

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

10

Conclusions

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

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

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

21 A univariate meta-regression model with consonant score against duration of implant
22 use for postlingually deaf adults, indicated that duration of implant use predicts a substantial
23 portion of their consonant identification ability. No statistical significance was found using
24 this model.

1 Tests with mono- and bisyllabic nonsense syllables have been employed in research
2 studies on CI users' speech perception for several decades. This kind of studies expose
3 information about the hearing of Cochlear implanted patients which the standard test batteries
4 in most audiological clinics do not reveal, information that is very useful for the mapping of
5 CIs and for the planning of habilitation and rehabilitation therapy. Such tests may also give
6 valuable information for further development of CI-technology. We therefore propose that
7 nonsense syllable tests be used as part of the standard test battery in audiology clinics when
8 assessing the speech perception of CI users.

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Table 1

PICOS Criteria for Inclusion in the Systematic Review and Meta-analysis

Acronym	Definition	Application of the criteria on the present study
P	Participants	Adults and/or children with one or two multi-channel CIs
I	Intervention	None
C	Control	Studies included both with and without control group
O	Outcomes	Consonant and/or vowel identification scores, measured by nonsense words
S	Study designs	Cross-sectional studies, longitudinal studies, case studies ($N \geq 3$)

Note. PICOS = Participants, Intervention, Control, Outcomes, and Study designs. Adapted from “The PICO Strategy for the Research Question Construction and Evidence Search,” by C. M. C. Santos, C. A. M. Pimenta, & M. R. C. Nobre, 2007, *Revista Latino-Americana de Enfermagem*, 15(3), pp. 508-511; CI = Cochlear Implant.

Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Arisi et al. (2010)	45	0	Italian	VCV	–	13.4 (2.6)	> 3	–	53.5 (33.6)	–	–
Baskent and Shannon (2004)	6	0	English (USA)	aCa	20	38.3 (13.6)	3.0 (1.5)	–	63.6 (21.7)	–	–
Bhattacharya and Zeng (2007)	7	6	English (USA)	aCa	20	63.3 (10.7)	3.4 (1.8)	–	68.4 (23.6)	–	–
Blamey, Dickson, and Grant (2004)	4	0	English (Australia)	aCa	16	54.0 (21.6)	3.3 (2.6)	–	71.1 (20.9)	–	–
Chatterjee and Peng (2008)	10	4	English (USA)	VCV	20	53.0 (16.5)	7.0 (5.0)	–	66.0 (17.0)	–	–
Cosendai and Pelizzone (2001)	3	0	French (Switzerland)	aCa and V	14 (VCV and 7 (V))	32.0 (12.8)	10.0 (4.4)	95 (2.7)	88.0 (1.0)	–	–

Note. The means and SDs are given with one decimal, except when the included articles reported these values without decimals. CI = Cochlear Implant; NH = Normally Hearing; VCV = Vowel–Consonant–Vowel; aCa = a–Consonant–a; V = Vowel.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	N		Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
	CI	NH						Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Desai, Stickney, and Zeng (2008)	8	14	English (USA)	VCV	20	62.5 (13.9)	3.8 (3.5)	–	49.6 (26.7)	–	–
Donaldson and Krefl (2006)	20	0	English (USA)	aCa, iCi, uCu, Ca, Ci, Cu	19	55.2 (11.4)	3.3 (3.6)	–	59.8 (13.9)	–	–
Dorman, Dankowski, McCandless, and Smith (1989)	10	0	English (USA)	aCa	16	Adult	–	–	58.1 (9.8)	–	–
Dorman and Loizou (1996)	7	0	English (USA)	aCa	16	Adult	> 4	–	51 (9)	–	–
Dorman et al. (1990)	10	0	English (USA)	aCa	16	Adult	–	–	58.2 (9.7)	41.3 (17.5)	NU-6

Note. 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.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	N		Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
	CI	NH						Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Doyle et al. (1995)	14	0	English (USA)	iCi	14	54.3 (15.9)	1.0 (0.6)	–	52.7 (17.2)	–	–
Friessen, Shannon, Baskent, and Wang (2001)	19	5	English (USA)	aCa	14	59.0 (13.3)	2.6 (2.2)	–	53.2 (14.4)	44.5 (20.2)	CNC
Fu (2002)	9	0	English (USA)	aCa	16	46.9 (9.3)	8.6 (2.5)	–	59.1 (20.3)	–	–
Fu and Shannon (2000)	6	0	English (USA)	aCa	16	53.0 (12.4)	5.3 (2.3)	–	67.8 (11.7)	–	–
Galvin, Fu, and Nogaki (2007)	11	9 ¹	English (USA)	aCa	20	49.0 (14.9)	7.3 (4.8)	–	49 (14.9)	–	–

Note. CNC = The Consonant–Vowel Nucleus–Consonant Test.

¹ Not tested with the consonant test.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Gani, Valentini, Sigrist, Kos, and Boex (2007)	4	0	French (Switzerland)	aCa, V	14 (aCa) and 7 (V)	46.8 (15.3)	1.4 (0.6)	67.5 (12.1)	64.2 (18.8)	–	–
Guevara, Grech, Gahide, and Gallego (2015)	8	0	French (France)	VCV	16	49.3 (8.7)	2.5 (1.7)	–	51.8 (19.0)	–	–
Guevara, Hoen, Truy, and Gallego (2016)	16	0	French (France)	VCV	16	48.8 (14.2)	5.1 (3.7)	–	42.5 (21.6)	–	–
Han et al. (2016)	10	11 ²	English (USA)	aCa	16	45.1 (18.2)	6.1 (4.0)	–	74 (21.1)	–	–
Incerti, Ching, and Hill (2011)	15	0	English (Australia)	aCa	24	Adult	4.2 (–)	–	68.4 (18.7)	–	–

² Not tested with the consonant test.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Ito, Tsuji, and Sakakihara (1994)	10	0	Japanese	V, aCa	5 (V), 13 (aCa)	Adult	–	87.7 (10.5)	41.7 (11.2)	–	–
Kirk et al. (1992), Sample A	10	12	English (USA)	wVb, bVb	8	47.3 (9.7)	1.7 (1.3)	50.5 (4.8)	–	22.8 (17.0)	NU-6
Kirk et al. (1992), Sample B	11	12	English (USA)	wVb, bVb	8	53.4 (17.3)	1.8 (1.6)	52 (4.0)	–	14.2 (16.1)	NU-6
McKay et al. (1992)	4	0	English (Australia)	aCa	12	45.0 (16.9)	2.7 (1.7)	–	77 (9.7)	57.6 (26.6)	NU-6
Meyer, Frisch, Pisoni, Miyamoto, and Svirsky (2003)	26	0	English (Australia)	aCa	24	Adult	>11 months	–	42.3 (22.2)	42.3 (22.2)	CNC

Note. wVb = w-Vowel-b; bVb = b-Vowel-b.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of		Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
					consonants and vowels in the test					Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	
Munson et al. (2003), Sample A	14	0	English (USA)	aCa	19		41.4 (10.3)	3.6 (3.5)	–	78.5 (6.1)	66.6 (17.7)	NU-6
Munson et al. (2003), Sample B	16	0	English (USA)	aCa	19		55.1 (12.2)	4.3 (4.1)	–	46.9 (13.0)	26.8 (18.5)	NU-6
Nie, Barco, and Zeng (2006)	5	0	English (USA)	aCa	20		35.8 (12.8)	4.6 (1.1)	–	64 (14.7)	–	–
Pelizzzone et al. (1999)	12	0	Albanian, French, German, Italian, Russian, Spanish, Swahili	aCa, V	14 (aCa), 7 (V)		43.3 (16.5)	5.1 (3.0)	78.3 (17.2)	65.6 (24.1)	–	–
Sagi et al. (2009)	11	16	English (USA)	aCa	16		50.4 (14.5)	3.6 (1.9)	–	43.1 (22.6)	38.6 (21.1)	CNC

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Shafiro, Gygi, Cheng, Vachhani, and Mulvey (2011)	17	0	English (USA)	aCa	20	55.0 (11.2)	3.2 (2.1)	–	51 (24)	51.8 (30.5)	CNC
Shallop, Arndt, and Turnacliif (1992)	7	0	English (USA)	aCa	14	58.4 (14.0)	1 (0)	–	50.6 (19.0)	21.2 (12.9)	NU-6
Shannon, Cruz, and Galvin 3rd (2011)	7	0	English (USA)	aCa	20	48.3 (9.1)	1.0 (0.3)	–	62.7 (7.3)	66.4 (17.9)	CNC
Shannon, Galvin III, and Baskent (2002)	6	6 ³	English (USA)	aCa	14	52.2 (11.1)	5.0 (2.9)	–	67.6 (18.5)	44 (22.5)	NU-6

³ Tests performed using a CI-simulator and the test results therefore not included.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Sheffield and Zeng (2012)	8	8	English (USA)	aCa	20	58.6 (11.4)	4.4 (2.0)	–	59.1 (5.2)	–	–
Singh, Kong, and Zeng (2009)	5	0	English (USA)	aCa	20	68.8 (7.6)	3.0 (2.6)	–	72.6 (16.1)	–	–
Skinner, Arndt, and Staller (2002)	56	0	English (USA)	aCa	14	54.4 (17.1)	–	–	66.6 (20.7)	43.7 (22.7)	CNC
Skinner, Holden, et al. (2002)	12	0	English (USA and Australia)	aCa	14	50.9 (22.6)	Short	–	64.6 (14.6)	–	–
Stacey et al. (2010)	11	0	English (UK)	aCa	20	49.1 (19.5)	5.7 (2.7)	–	39.8 (18.8)	–	–
Svirsky, Sagi, Meyer, Kaiser, and Teoh (2011)	28	0	English (USA)	aCa	24	49.7 (15.9)	3.3 (2.5)	–	45.1 (20.7)	–	–

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	<i>N</i>		Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
	CI	NH						Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Teoh, Neuburger, and Svirsky (2003)	15	0	English (USA)	aCa	24	52.9 (12.7)	3.6 (1.8)	–	46.7 (18.1)	–	–
Throckmorton and Collins (1999)	7	0	English (USA)	aCa	14	54.6 (11.6)	6.9 (2.8)	–	34 (14.2)	14.9 (10.7)	NU-6
Tye-Murray, Lowder, and Tyler (1990)	5	0	English (USA)	iCi	14	Adult	>10 months	–	41 (13.1)	27.6 (13.2)	NU-6
Tye-Murray, Witt, and Castelloe (1996)	40	0	English (USA)	aCa	13	51.5 (–)	3.6 (2.2)	–	66 (20)	–	–

Note. PBK = The Phonetically Balanced Kindergarten Word Test.

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Table 2

Study Characteristics, Task Characteristics, and Results for the 50 Included Studies

Authors	CI	NH	Language of participants	Stimulus context	Number of consonants and vowels in the test	Age (years) of implantation, <i>M(SD)</i>	Duration (years) of implant use, <i>M(SD)</i>	Speech sound score (%)			Name of test
								Vowels, <i>M(SD)</i>	Consonants, <i>M(SD)</i>	Score (%), <i>M(SD)</i>	
Tyler (1990)	5	0	English (Australia)	iCi	13	7.4 (1.9)	1.1 (0.6)	–	30 (13.2)	16 (20.3)	PBK
Tyler and Moore (1992), Sample A	10	6	German	iCi	13	43.8 (9.5)	2.0 (0.6)	–	31.1 (7.0)	–	–
Tyler and Moore (1992), Sample B	19	2	English (USA)	iCi	13	37.5 (13.5)	2.4 (2.8)	–	43.9 (10.6)	–	–
Van Wieringen and Wouters (1999)	25	20	Flemish	aCa	16	43.4 (14.2)	2.1 (1.4)	–	33 (13)	–	–
Wouters and van den Bergh (2001)	4	0	Flemish	aCa	16	39.8 (10.4)	2.0 (1.4)	–	63.3 (7.9)	–	–

Table 3

Means, SDs, and Ranges of the Study Variables for the Pre- and Postlingually deaf CI Users

	Postlingually deaf			Prelingually deaf			Total		
	<i>M</i> (<i>SD</i>)	<i>N</i>	Range (%)	<i>M</i> (<i>SD</i>)	<i>N</i>	Range (%)	<i>M</i> (<i>SD</i>)	<i>N</i>	Range (%)
Study variables	(%)			(%)			(%)		
Consonant score	58.4 (26.3)	44	18.7–91.6	46.7 (11.5)	6	36.0–76.0	56.3 (23.1)	48	30.0–88.0
Vowel score	76.8 (26.5)	5	50.5–95.0	67.7 (0.0)	1	–	72.4 (23.1)	6	50.5–95.0
Real word monosyllable score	40.4 (16.5)	14	14.9–66.6	–	–	–	37.2 (16.8)	17	14.2–66.6

Note. In three of the studies the real word monosyllable scores could not be separated into separate scores for the groups of pre- and postlingually deaf CI-users; CI = Cochlear Implant.

Table 4

Description of the Articles Presenting Consonant Confusions in Matrices

Authors	Consonant context	Number of consonants	Number of participants	Language
Donaldson and Kreft (2006)	Ca, Ci, Cu, aCa, iCi and uCu,, both female and male reader in each condition	19	20	English (USA)
Dorman and Loizou (1996)	aCa	16	7	English (USA)
Dorman et al. (1990)	aCa	16	10	English (USA)
Doyle et al. (1995)	iCi	14	14	English (USA)
Incerti et al. (2011)	aCa	24	15	English (Australia)
McKay et al. (1992)	aCa	12	4	English (Australia)
Munson et al. (2003)	aCa	19	30	English (USA)
Teoh et al. (2003)	aCa	24	14	English (USA)
Tyler (1990)	iCi	13	4	English (Australia)
Tyler and Moore (1992)	iCi	13	28	English (USA)
Van Wieringen and Wouters (1999)	aCa	16	25	Flemish

1 *Note.* Ca = Consonant–a; Ci = Consonant–i; Cu = Consonant–u; aCa = a–Consonant–a; iCi = i–Consonant–i; uCu = u–

2 Consonant–u.

1 Table 5

2 *Overview of the Three Most Frequently Correctly Identified Consonants in the Included*

3 *Studies*

Stimulus	Index of correct identifications (%)
/t/	18.1
/k/	17.7
/m/	14.8
/n/	10.6
/p/	9.7
/z/	8.9
/d/	7.8
/b/	7.0
/s/	5.3

Note. The three most frequently correctly identified consonants in each study were picked, assigned to an index weighed by the number of participants in the study, added together with the results from the other studies, and included in this table. The percentages in the second column were calculated by dividing the number of correct identifications of each consonant by the total number of correct responses. The consonant with the highest percentage was the most frequently correctly identified of the nine consonants.

The consonants are arranged in descending order according to percentage of correct identification.

1 Table 6

2 *Confusion Matrix of the Three Most Frequently Confused Consonants Pooled Across 13*

3 *Studies*

Stimulus	Response (%)								Sum (%)	
	/p/	/t/	/k/	/b/	/d/	/m/	/n/	/s/		/z/
/p/		11.4	6.7					0.8		18.9
/t/	7.5		10.1							17.6
/k/	3.7	18.5								22.2
/b/					3.0		4.3			7.3
/d/				5.6						5.6
/m/							18.1			18.1
/n/						7.5				7.5
/s/										0.0
/z/								2.8		2.8

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 rightmost column were calculated by dividing the number of confusions in each table cell by the total number of confusions. The cell with the highest percentage shows the most frequent consonant confusion of the 13 studies.

Table 7

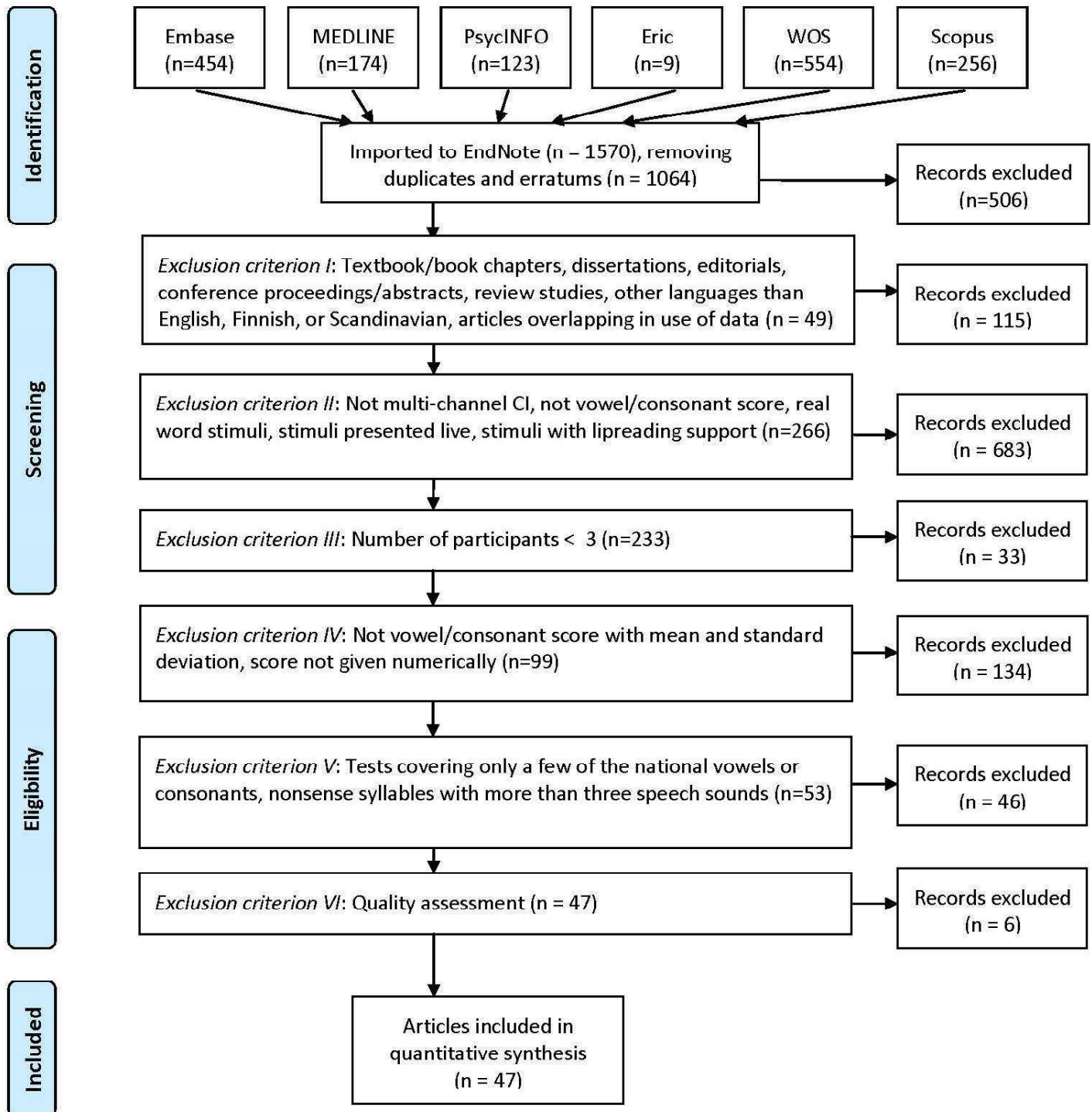
Means, SDs, and Ranges for the Moderator Variables for the Pre- and Postlingually deaf CI Users

Moderator variable	Postlingually deaf			Prelingually deaf			Total		
	<i>M (SD)</i> (years)	<i>N</i>	Range (years)	<i>M (SD)</i> (years)	<i>N</i>	Range (years)	<i>M (SD)</i> (years)	<i>N</i>	Range (years)
Age at implantation	49.7 (18.3)	37	7.9–68.8	39.9 (6.8)	6	6.8–31.5	48.0 (22.5)	42	7.4–68.8
Duration of implant use	3.4 (1.6)	35	1.0–10.0	6.0 (4.6)	5	0.8–11.5	3.4 (1.6)	39	1.0–10.0

Note. CI = Cochlear Implant.

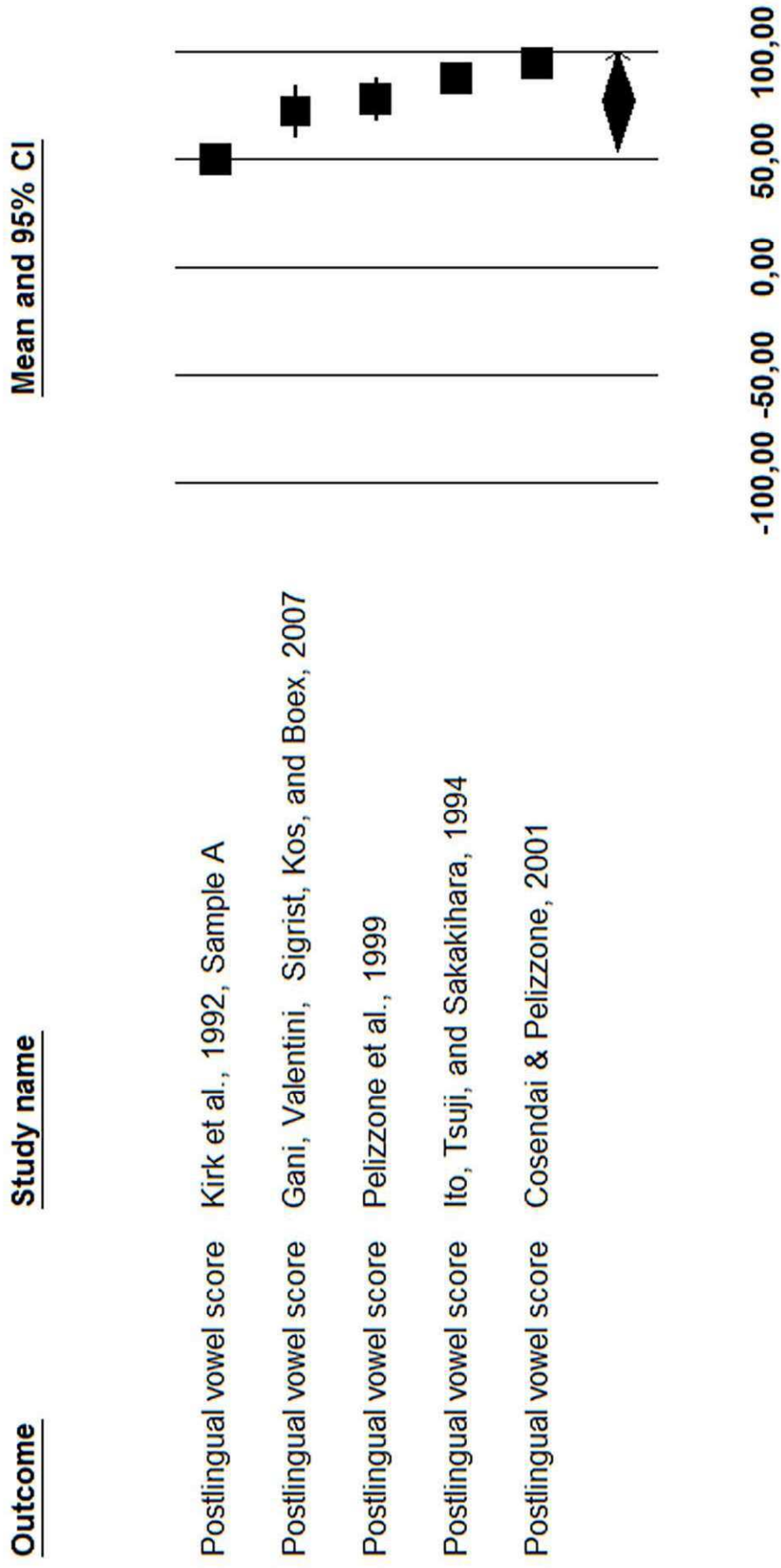
Flow Diagram – Search of “nonsense words” with synonyms and “cochlear implants (CIs)” with synonyms.

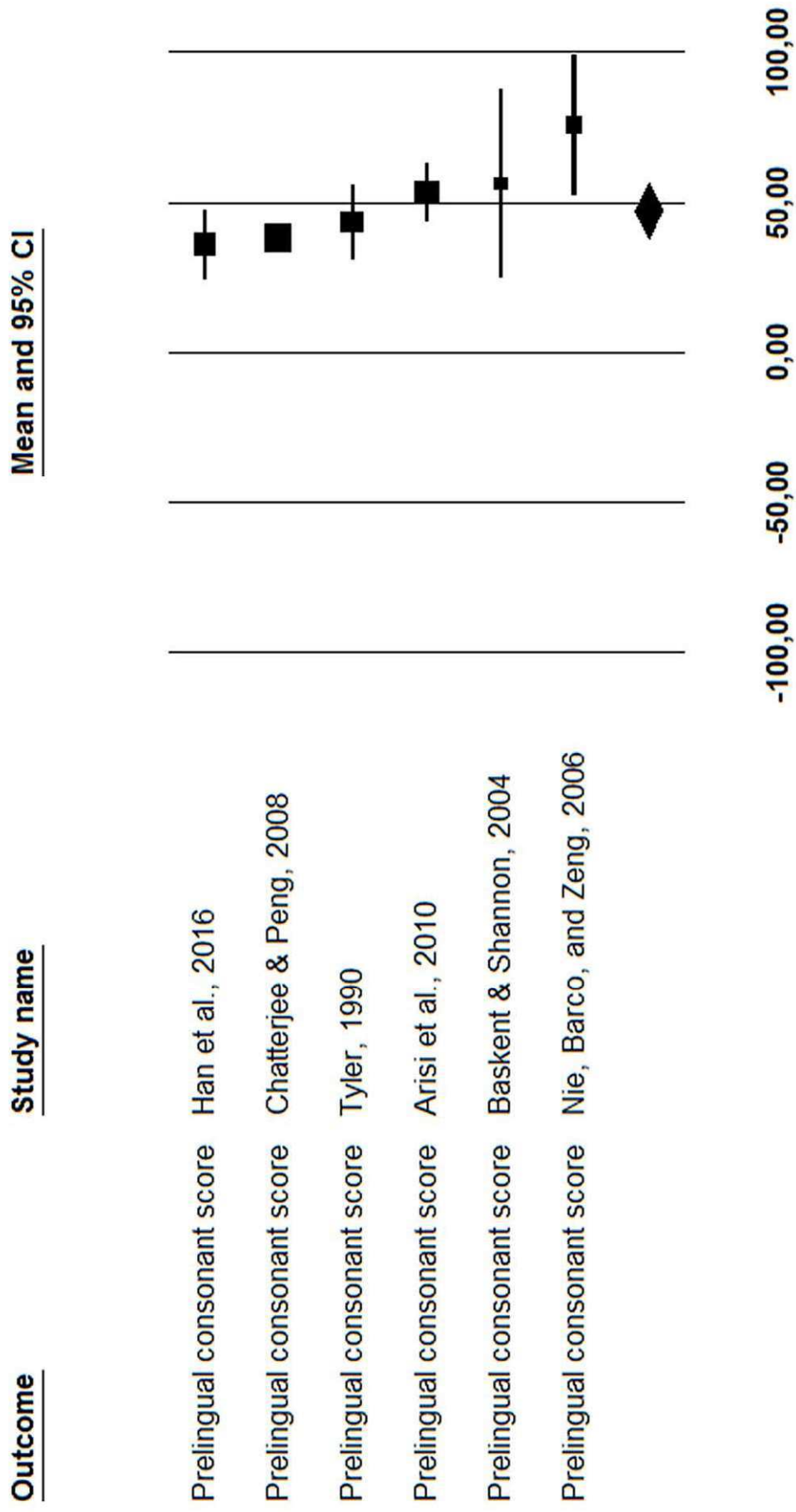
Search dates: 08-13-14, 04-06-15 and 10-09-16.

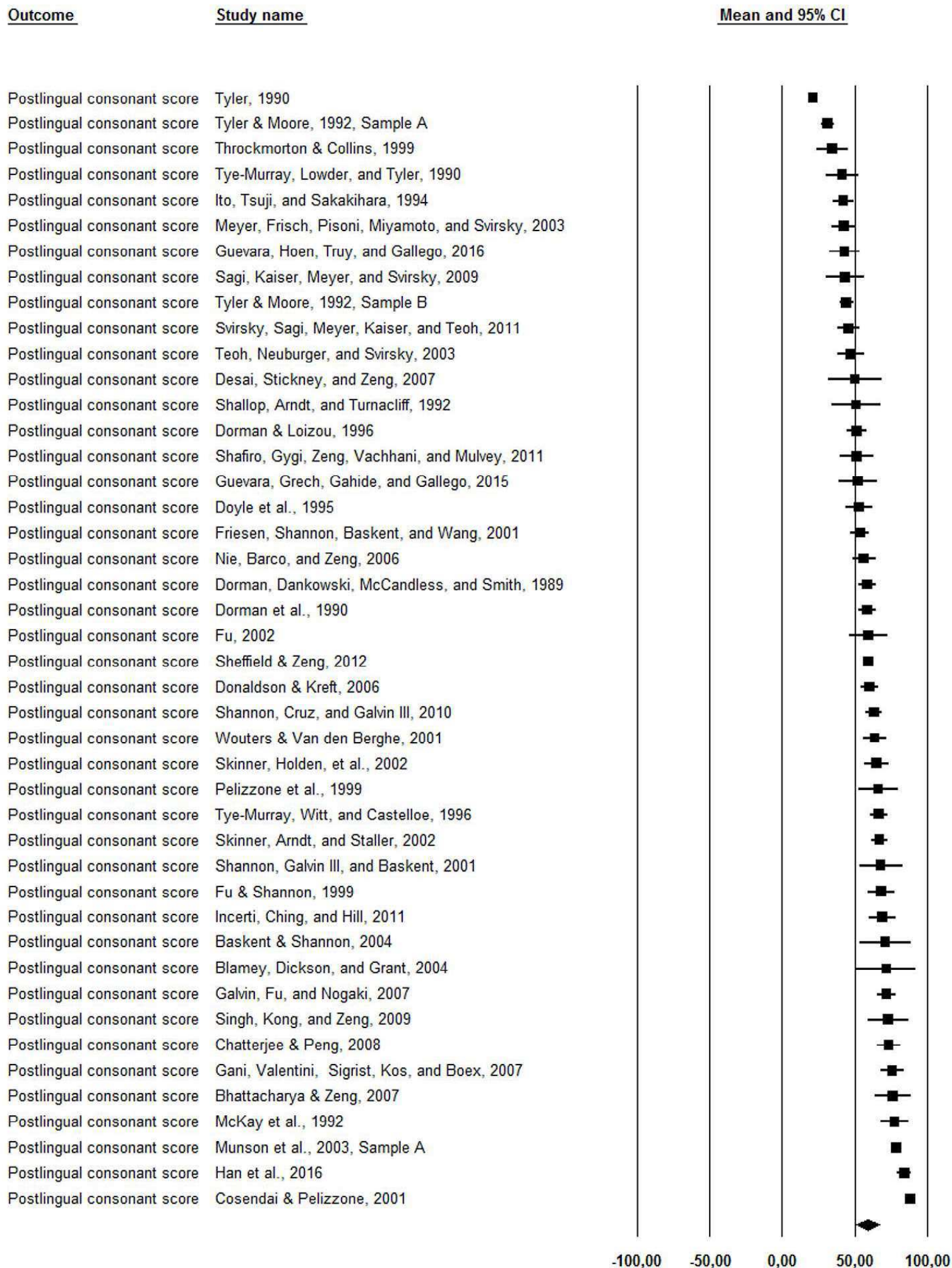


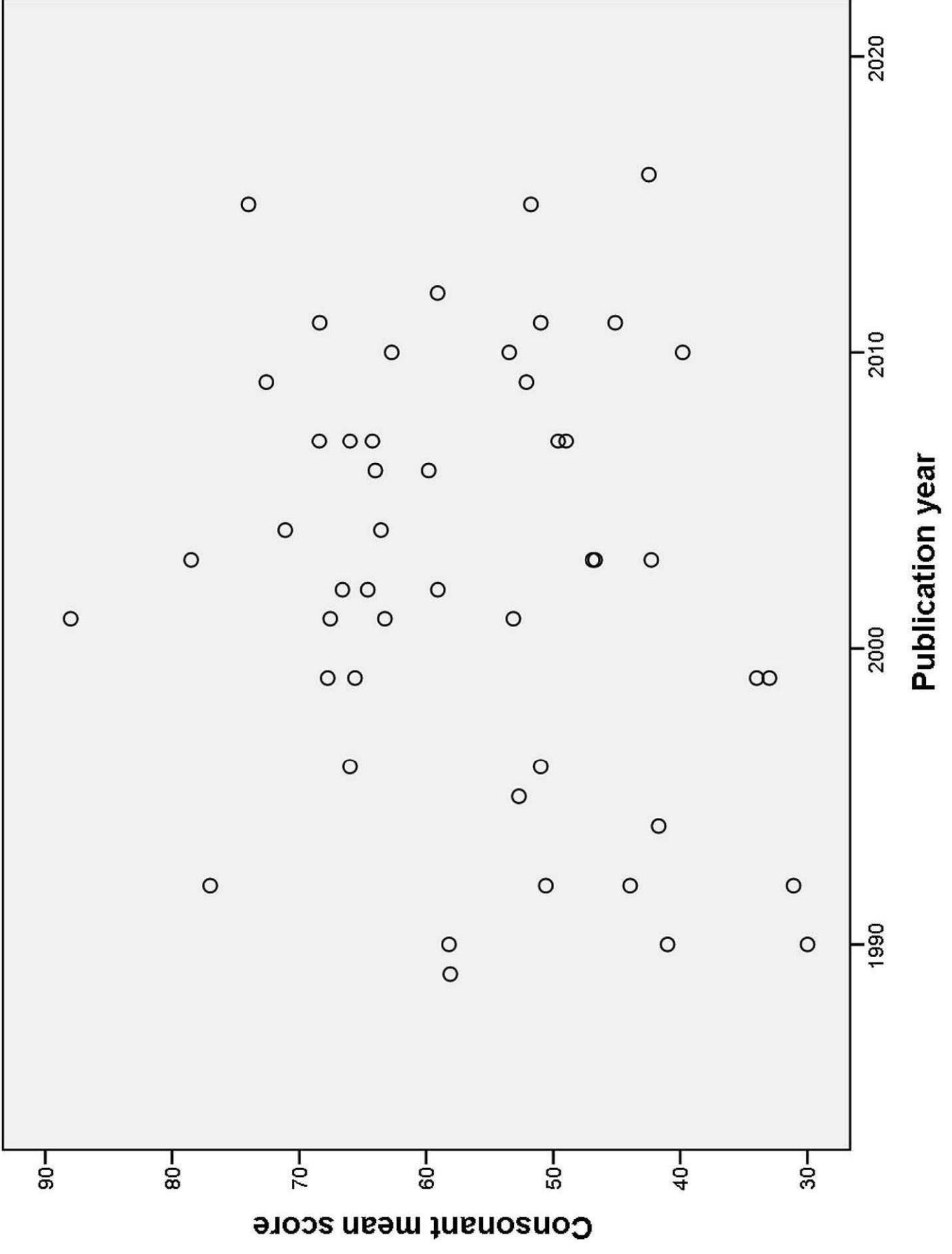
From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit www.prisma-statement.org.









Appendix 1

Search syntax

Database: Embase Classic+Embase 1947 to 2014 July 02

Search Strategy:

- 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)

Database: Ovid MEDLINE® In-Process & Other Non-Indexed Citations and Ovid

MEDLINE® <1946 to Present>

Search Strategy:

- 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 [Rehabilitation, 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 or/6-9,21,28 (12981)
- 30 3 or 4 or 5 (2829)
- 31 29 and 30 (144)

Database: PsycINFO <1806 to June Week 4 2014>

Search Strategy:

- 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)
- 7 ((cochlear or auditive or auditory or hearing) adj2 (implant* or prosthes*)).mp.
(2136)
- 8 exp Prostheses/ or “prostheses and implants”.mp. (2236)
- 9 exp Partially Hearing Impaired/ or exp Hearing Disorders/ or exp Hearing Aids/ or
sensory aids.mp. (17231)
- 10 (implant* or prosthes*).mp. (12952)
- 11 8 or 9 or 10 (28173)
- 12 cochlea*.mp. or cochlea/ [mp=title, abstract, heading word, table of contents, key
concepts, original title, tests & measures] (5518)
- 13 11 and 12 (2795)
- 14 (implant* or prosthes*).mp. (12952)
- 15 exp Hearing Aids/ (2776)
- 16 exp Deaf/ or exp Partially Hearing Impaired/ or exp Hearing Disorders/ (16099)
- 17 15 or 16 (17202)
- 18 14 and 17 (2009)
- 19 or/6-7,13,18 (2854)
- 20 3 or 4 or 5 (6354)
- 21 19 and 20 (56)

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.

Search Strategy:

-
- 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 prothes*)).mp. (499)
 - 8 “protheses 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 prothes*).mp. (2727)
 - 9 Cochlea*.mp. or Cochlea/ (2065)
 - 10 8 and 9 (2032)
 - 11 (implant* or prothes*).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)

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

Search Strategy:

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 prothes*))

10 TS=(“protheses and implants” or “sensory aids” or “hearing aids” or “hearing loss” or “hearing disorders” or (implant* or prothes*))

11 TS=(Cochlea*)

12 #11 AND #10

13 TS=(implant* or prothes*)

14 TS=(“hearing aids” or “hearing loss” or “hearing disorders” or “hearing impair*”)

15 #14 AND #13

16 #15 OR #12 OR #9 OR #8

17 #16 AND #7

Database: Scopus (Elsevier)

Search strategy:

((TITLE-ABS-KEY("Cochlear implant*")) OR

(TITLE-ABS-KEY((cochlear or auditive or auditory or hearing) PRE/2 (implant* or prothes*))) or ((TITLE-ABS-KEY("protheses and implants" or "sensory aids" or "hearing aids" or "hearing loss" or "hearing impaired persons" or "hearing disorders" or (implant* or prothes*))) and

(TITLE-ABS-KEY(cochlea*))) or

((TITLE-ABS-KEY(implant* or prothes*)) 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(consonant 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*")))))