This item is the archived peer-reviewed author-version of:

Cognitive outcomes after cochlear implantation in older adults : a systematic review

Cognitive outcomes after cochlear implantation in older adults:

A systematic review

Annes J. Claes[1,2*], Paul Van de Heyning[1,2], Annick Gilles[1,2,3], Vincent Van Rompaey[1,2], Griet Mertens[1,2]

[1]*Department of Otorhinolaryngology, Head and Neck Surgery, Antwerp University Hospital (UZA), Antwerp, Belgium*

[2]*Experimental Laboratory of Translational Neurosciences and Dento-Otolaryngology, Faculty of Medicine and Health Sciences, University of Antwerp (UA), Antwerp, Belgium*

[3]*Department of Human and Social Welfare, University College Ghent, Ghent, Belgium*

*Corresponding author

Annes J. Claes

Antwerp University Hospital (UZA)

Department of Otorhinolaryngology, Head and Neck Surgery

Wilrijkstraat 10

2650 Edegem

Belgium

0032 3 821 58 38

annes.claes@uza.be

paul.vandeheyning@uza.be

annick.gilles@uza.be

vincent.vanrompaey@uza.be

griet.mertens@uza.be

Biographical notes:

Annes Claes is doctoral researcher at the University of Antwerp and clinical audiologist at the Antwerp University Hospital. Her main research topic is cognition in severely hearing-impaired older adults and cochlear implant recipients.

Paul Van de Heyning (MD, PhD) is chairman of the Department of Otorhinolargngology and Head and Neck Surgery at the Antwerp University Hospital and is professor at the University of Antwerp.

Annick Gilles (PhD) is a post-doctoral researcher at the University of Antwerp and tinnitus expert at the Antwerp University Hospital. She is associated professor since 2017.

Vincent Van Rompaey (MD, PhD) has been appointed as an otolaryngologist since 2013 at the Antwerp University Hospital. He performed his doctoral research on quality assurance in middle ear surgery and was appointed as an assistant professor at the University of Antwerp.

Griet Mertens (PhD) holds a position as associated professor at the University of Antwerp since 2017. She completed her PhD on Single-Sided Deafness and partial deafness at the Antwerp University in 2015.

Disclosure of interest:

The authors report no conflict of interest.

Cognitive outcomes after cochlear implantation in older adults:

A systematic review

Objectives: To critically assess the current status of the literature on cognitive outcomes after cochlear implantation in older adults.

Methods: Studies were identified by searching MEDLINE (PubMed) and Cochrane Library, and checking reference lists of relevant articles. No restrictions were imposed regarding language, publication date, or publication status. Eligibility criteria were as follows: (1) the study sample included older adults aged 50 or over with severe to profound bilateral hearing loss, (2) the participants received a multi-electrode cochlear implant, and (3) a cognitive test was performed before and after implantation. Risk of bias was assessed with respect to: (A) the suitability of the cognitive tests to examine cognition in hearing-impaired subjects, (B) the control of practice effects, (C) statistical methods, and (D) other sources of bias.

Results: Out of 2716 retrieved records, six were found eligible, examining a total of 166 patients. Five of these studies reported improvements in cognition postimplantation and one study did not observe significant changes. Control of practice effects and the statistical methods were the most common origin of observed bias.

Discussion: The currently reviewed studies performed pioneering work and are indispensable for the field. However, they do not provide inconclusive evidence of improved cognitive outcomes after cochlear implantation in older adults.

Conclusion: Well-designed studies with long follow-up periods are imperative to verify whether cochlear implantation influences cognition in older adults. New research is stimulated to use appropriate cognitive assessment tools for hearing-impaired individuals, to control for practice effects, and to perform appropriate statistical tests.

1. Introduction

The relation between hearing loss and cognitive decline in older adults has been established by an increasing number of prospective, longitudinal studies, indicating that older hearing-impaired adults present an accelerated cognitive decline compared to normal-hearing peers (Gallacher et al., 2012; F. R. Lin et al., 2011; F. R. Lin et al., 2013; Valentijn et al., 2005). For instance, Gallacher, et al. (2012) demonstrated that baseline auditory threshold is associated with incident dementia and cognitive decline in more than 1000 older men over a period of 17 years. Moreover, the association between degree of hearing loss and rate of cognitive decline appeared to be linear, suggesting that individuals with a severe hearing loss are at greater risk of cognitive decline than mildly hearing-impaired peers (F. R. Lin, et al., 2013). Although these studies point out that hearing loss is a risk factor of cognitive decline, the underlying explanatory mechanism of this relation remains an open question. Hearing loss may be a determinant of dementia or may negatively affect *performance* on cognitive tests, but alternatively, prodromal dementia may cause hearing loss as well. Another explanation is that hearing loss and cognitive decline share a common neurodegenerative etiology (Gallacher, et al., 2012).

Given the relation between hearing loss and cognitive decline, researchers have been interested in the effect of restoring hearing ability on cognitive functions in older adults. Some articles reported promising results with hearing aids (Acar, Yurekli, Babademez, Karabulut, & Karasen, 2011; Amieva et al., 2015; Choi, Shim, Lee, Yoon, & Joo, 2011; Dawes et al., 2015). However, other studies did not find any effect of hearing aids on cognition (Valentijn, et al., 2005; van Hooren et al., 2005). For persons with advanced hearing loss, for whom hearing aids do not provide sufficient benefit, a cochlear implant (CI) may be a good solution. It is generally considered a safe and efficient treatment, even in the elderly (Castiglione et al., 2015; Clark et al., 2012; Cosetti and Lalwani, 2015). Nevertheless, cochlear implantation requires surgery and anaesthesia, which may lead to postoperative cognitive dysfunction in some older patients (Claes et al., 2018). As individuals with severe hearing loss are at greater risk of cognitive decline than individuals with a mild or moderate hearing loss (F. R. Lin, et al., 2013), cochlear implantation has a greater potential of positively affecting cognition than hearing aids. With regard to the effects of cochlear implantation on cognitive decline in older adults, the authors propose three hypotheses, schematically presented in Figure 1. According to the first, receiving a CI does not influence the cognitive trajectory in hearing-impaired older adults. The accelerated cognitive decline continues in the same way as it did prior to the implantation and the distinction in cognitive performance between normal-hearing and hearing-impaired individuals continues to increase (Figure 1A). The second hypothesis involves a more positive effect of hearing rehabilitation on cognition. The CI stops the acceleration of the cognitive decline and induces an age-expected speed of decline. However, the hearing-impaired older adults do not bridge the gap with the normal-hearing older adults in terms of cognition (Figure 1B). The third hypothesis states that the use of a CI improves cognition and induces a

catching-up with the normally-hearing older adults, resulting in an age-expected cognitive trajectory (Figure 1C). In this systematic review, the current status of the literature on the cognitive outcomes after cochlear implantation in older adults is evaluated and the evidence for any of the three proposed hypotheses is critically assessed.
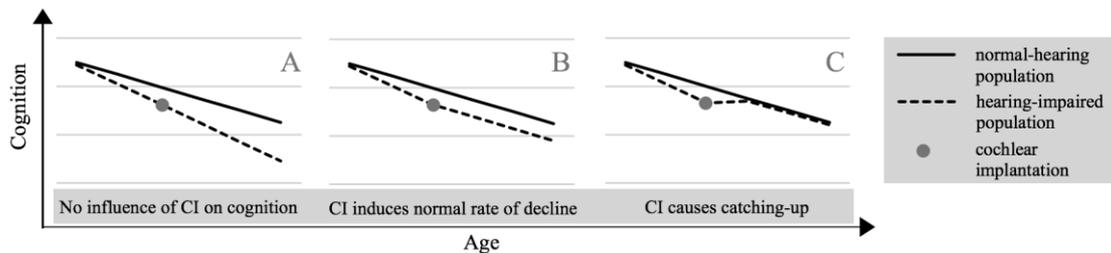

Figure 1. Schematic representation of the three hypotheses on the effect of cochlear implantation on cognitive decline in older adults. The solid line indicates normal cognitive decline in the aging normally-hearing population and the dashed line indicates the cognitive evolution before and after cochlear implantation (marked by the grey dot) in hearing-impaired older adults. (A) no effect of cochlear implantation on the cognitive trajectory in the older hearing-impaired population. The accelerated cognitive decline continues equally as prior to the implantation, resulting in an increasing gap with the normally-hearing population. (B) the acceleration in cognitive decline is stopped after cochlear implantation and an age-expected speed of decline is induced. The gap with the normally-hearing population is not bridged. (C) cochlear implantation improves and restores cognition to an age-expected level, with an age-expected speed of decline.

2. Methods

This systematic review was performed using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009). It aims to review the existing literature on the cognitive outcomes of cochlear implantation in older adults.

2.1. Eligibility criteria

The following items were used as criteria for eligibility:

- *Participants*: The study population consists of, or includes, older adults aged 50 or over with severe to profound bilateral hearing loss with postlingual onset, for which a CI is indicated according to national criteria.
- *Intervention*: Cochlear implantation with a multi-electrode implant.
- *Comparator*: No constrictions are imposed.

- *Outcomes*: Change in performance on cognitive tests (not questionnaires), that assess cognition in general or one or more cognitive domains, after cochlear implantation compared to baseline.
- *Study design*: Longitudinal studies with at least one baseline measurement before implantation and one measurement after implantation. Studies may be either prospective or retrospective and may include a control group.

Only primary research was accepted to avoid including duplicate data. Reviews and letters to the editor were excluded. No restrictions were imposed with regard to language, publication date, or publication status.

2.2. Search strategy

Studies were identified by searching electronic databases, MEDLINE (PubMed) and Cochrane Library, and checking reference lists of relevant articles. Literature search started on the 30th of January, 2018 and was completed on the 8th of February, 2018. The MEDLINE (PubMed) and Cochrane Library search strategies are available in Appendix A and B. Title and abstract of the obtained records were screened and full texts were retrieved and analyzed if the record passed the screening phase. Study selection was conducted independently by two authors, AC and GM. Potential disagreements were resolved by consensus.

2.3. Information extraction

Information was extracted from the selected studies on (1) study design, (2) characteristics of the participants (number, sex, age, hearing impairment, duration of hearing loss, use of hearing aids, level of education etc.), (3) type of outcome measurements (cognitive test, cognitive domains assessed by the test, adaptation for hearing-impaired individuals), (4) statistical method, and (5) results (change in cognitive performance after cochlear implantation). The risk of bias (i.e. quality) in individual studies was assessed with respect to four topics. The first topic involves the suitability of the cognitive tests to assess cognition in severely hearing-impaired individuals (Risk of bias A). A severe hearing impairment may negatively affect the performance on a cognitive test (Dupuis et al., 2015), as the to-be-repeated or to-be-remembered items may not be well perceived by the participant. Furthermore, given the improvement in hearing abilities after cochlear implantation, a possible increase in performance on these cognitive tests may rather be attributed to the improved hearing than to an increase in cognition. Therefore, a cognitive tool which can be validly administered to hearing-impaired subjects should be selected or an existing cognitive test should be adequately adjusted for the sample. The second risk of bias discussed in this review is the control of practice effects (Risk of bias B). Indeed, all participants are at least assessed twice, once before and once after implantation. Hence, a possible improvement in cognition may be biased by a practice effect. Next, the statistical methods are considered as risk of bias (Risk of bias C) and finally, other sources of bias

(Risk of bias D) are taken into account.

3. Results

3.1. Study selection

Electronic database searching resulted in 2716 records, of which the vast majority was retrieved from MEDLINE (n=2706). No additional records were obtained by scanning the reference lists of the relevant articles. Four duplicates were identified and removed. After screening the title and abstract, 2689 records were found irrelevant and were therefore excluded. The full-text of 23 articles was further analyzed, applying the eligibility criteria listed above. Seventeen articles did not meet the inclusion criteria. Eleven of these studies only examined cognition before implantation, but not after implantation (Aplin, 1993; Gantz, Woodworth, Knutson, Abbas, & Tyler, 1993; Heydebrand, Hale, Potts, Gotter, & Skinner, 2007; Holden et al., 2013; Knutson et al., 1991; Kropp, Niederberger, & Gerber, 2000; Li et al., 2017; Parkin, Stewart, Dankowski, & Haas, 1989; Shipp, Nedzelski, Chen, & Hanusaik, 1997; Summerfield and Marshall, 1995; van Dijk et al., 1999). Only qualitative measurements were performed in one study (Hogan, 1997) and another study was not longitudinal, but cross-sectional (Capretta and Moberly, 2016). Crary, Wexler, Berliner, & Miller (1982) performed cognitive tests before and after cochlear implantation. However, the CIs used were single-electrode implants. Three other records were removed, since they did not involve primary research (Huber and Kaiser, 2017; Knopke and Olze, 2017; Miller et al., 2015). Eventually, six articles met the full inclusion criteria and thus, were included in the review (Ambert-Dahan et al., 2017; Castiglione et al., 2016; Cosetti et al., 2016; Jayakody et al., 2017; Mosnier et al., 2015; Sonnet et al., 2017) (Figure 2).
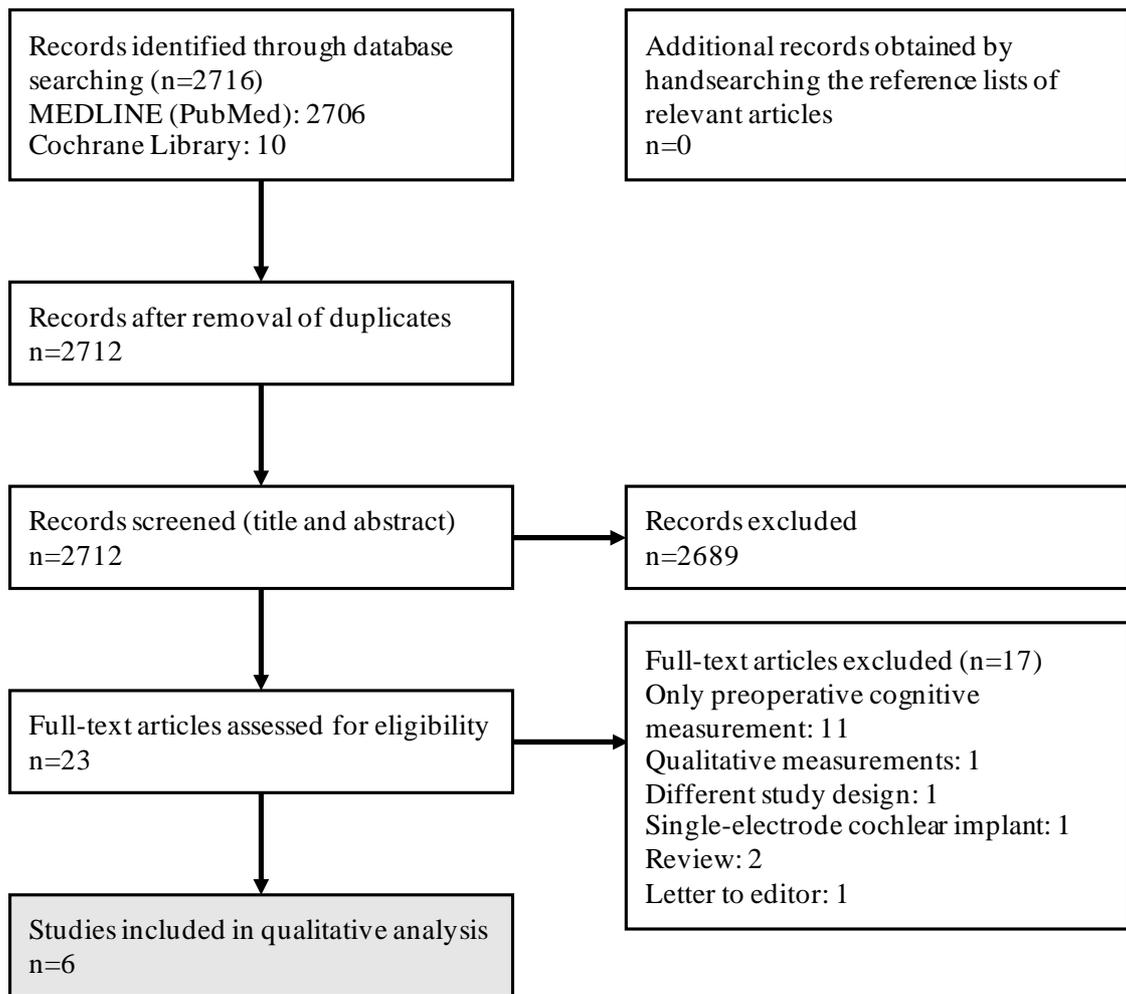
Figure 2. Flowchart of the study selection process.

3.2. Information extraction

All selected studies investigated cognition in severely to profoundly hearing-impaired older adults before and after cochlear implantation. Most studies were longitudinal cohort studies, assessing cognition among a cohort of CI recipients before and once or twice after implantation (Ambert-Dahan, et al., 2017; Cosetti, et al., 2016; Mosnier, et al., 2015; Sonnet, et al., 2017). The follow-up period ranged from 1 to 3.7 year. Castiglione, et al. (2016) included a cross-sectional normal-hearing control group, to which the CI recipients were compared postoperatively in terms of cognitive performance. In the study of Jayakody, et al. (2017) on the other hand, a control group was included and assessed longitudinally. The control group consisted of CI candidates, who met the criteria for cochlear implantation, but had to wait six to twelve months to receive their implant through the subsidized system. Overall, 166 patients were included, of which 77 (46.4%) were men and 89 (53.6%) were women. Five studies reported improvements in cognition after cochlear implantation (Ambert-Dahan, et al.,

2017; Castiglione, et al., 2016; Cosetti, et al., 2016; Jayakody, et al., 2017; Mosnier, et al., 2015). Only Sonnet, et al. (2017) described a stability of cognitive performances before and after implantation. A structured overview of the characteristics of the participants and the risks of bias for each study is presented in Table 1. Table 2 contains the cognitive outcome measurements used in the individual studies, along with the outcomes. The cognitive tests are classified according to the cognitive domain they mainly assess. The list of key cognitive domains is based on the Diagnostic and Statistical Manual of Mental Disorders (DSM-V) (Sachdev et al., 2014).

3.2.1. Ambert-Dahan – 2017

Ambert-Dahan, et al. (2017) included 18 adults between 23 to 83 years old, with postlingual severe to profound sensorineural hearing loss. The mean duration of profound hearing loss was 6.5 (±2.1) year (range: 0.3 to 35 year). The participants were excluded from the study in case of neurological, psychiatric or visual illness. All entered a specific auditory-cognitive training program, which was an integral part of the routine auditory rehabilitation (Table 1, Risk of bias D). This training program was aimed at developing speech perception with the CI and cognitive abilities involved in verbal processing (e.g. attention, verbal memory and mental flexibility). Participants' cognition was assessed prior to and twelve months after implantation by means of two cognitive screening tests, the Cognitive Disorders Examination (CODEX) (Belmin et al., 2007) and the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) (Appendix C). Both tests were reported to be adapted with visual adaptation on a screen, but detailed information on the adaptation is lacking (Table 1, Risk of bias A). Furthermore, no statistical analyses were performed with respect to the change in cognitive performance (Table 1, Risk of bias C), presumably due to the small sample size and the ordinal character of the CODEX results. The qualitative analyses indicated that four of the eight participants with abnormal scores before implantation, improved their cognitive performance into the normal range twelve months after implantation. On the other hand, three of the ten participants with normal preoperative cognitive scores demonstrated a decrease in performance, but remained in the normal range. No control group was included or no other attempts were made to control for possible practice effects (Table 1, Risk of bias B).

3.2.2. Castiglione – 2016

Castiglione, et al. (2016) investigated the effects of restoring hearing ability through hearing aids and CIs on cognitive functioning in older adults with varying degrees of hearing loss. The group of CI recipients, consisting of 15 participants, was administered the MoCA before and twelve months after implantation. It was reported that evaluation schedules and materials were tailored to the individual according to the hearing loss and hearing treatment program. However, no more information is given on this topic (Table 1, Risk of bias A). Ten out of thirty points to be obtained in the MoCA rely on hearing,

making this test susceptible for underestimating the cognitive performance in hearing-impaired individuals if no adequate adjustment is provided. Prior to implantation, the mean MoCA score was 25.7 (±3.6) and after implantation 27.2 (±3.7), which was a significant improvement (p<0.01). However, a parametric student's t test for paired data was used to analyze the difference in MoCA scores, which is suboptimal given the small sample size (Table 1, Risk of bias C). Twenty normal-hearing older adults took part in the study as the control group and were administered the MoCA once. The postimplantation MoCA scores of the CI recipients did not significantly differ from the MoCA score of the NH listeners. As the control group was only tested once, practice effects were not taken into account in the study (Table 1, Risk of bias B).

3.2.3.   Cosetti – 2016

In the longitudinal study of Cosetti, et al. (2016) seven elderly women with postlingual deafness were examined prior to implantation and on average 3.7 year (range: 2 to 4.1 year) after implantation. Patients with known neurologic disease, including dementia, cerebrovascular disease, or any process known to impair cognitive function were excluded. Twenty-nine years was the mean duration of severe hearing loss (range: 8 to 53 year). All participants underwent unilateral cochlear implantation (6 right, 1 left) without entering a postoperative rehabilitation program. An extensive cognitive test battery was administered, comprising the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1997), Trail Making Test (TMT) part A and B (Tombaugh, 2004), controlled oral word association test, the Boston naming test (Kaplan, Goodglass, & Weintraub, 1983) and the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) (Randolph, 1998) (Appendix C). Preoperatively, test instructions were given in oral and written format to avoid misunderstanding due to hearing loss. Yet, no further adjustments to the tests were reported, making it unclear whether the required adjustments were done (Table 1, Risk of bias A). Adjustments to the test items are imperative in case of several RBANS subtests, for instance List learning (remembering 10 words), Story memory (remembering a short story) and Digit span (recalling series of digits). Test results of all the subtests, 20 in total, were categorized on a 13-point ordinal continuum (-6 to 0 to +6) using standardized age-based norms. The change in score on this ordinal scale for each subtest was qualitatively analyzed both at the individual level and at the sample level (i.e. averaged over the seven participants). In 14 of 20 subtests (70%) improvements were observed at the sample level. Since only qualitative analyses were performed, it is unclear whether the described changes were significant or only reflect natural variation in performance (Table 1, Risk of bias C). Furthermore, no control group was included to account for a possible practice effect (Table 1, Risk of bias B). However, due to the long test interval of two to four years, a significant practice effect is rather unlikely. Another risk of bias is the large amount of missing data (Table 1, Risk of bias D). Twenty-seven patients were administered the cognitive test battery preimplantation, whereas only seven patients also took the postoperative assessment. Moreover, even among the seven included participants, only

three completed the full test battery at both evaluations.

3.2.4. Jayakody – 2017

Thirty-nine participants took part in the study of Jayakody, et al. (2017): 16 CI recipients and 23 CI candidates who had met the criteria for cochlear implantation but were to wait six to twelve months to receive the CI through the subsidized system. Cognition was evaluated by means of six subtests of the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Cambridge Cognition Ltd., 2012): the Attention switching, Delayed matching to sample, Paired associates learning, Verbal recognition memory, Reaction time and Spatial working memory task (Appendix C). The CANTAB is a nonverbal, computerized cognitive test battery (http://www.cambridgecognition.com/cantab), suitable for both normal hearing and hearing-impaired subjects (Table 1, Risk of bias A). It was administered at baseline and six and twelve months later. At the twelve-months measurement, only 11 out of 16 CI recipients and 11 out of 23 CI candidates completed the evaluation. This decrease in sample size was partly due to CI candidates receiving their CI after six months of waiting. The change in performance between baseline and six months differed significantly between both groups (CI recipients versus CI candidates) for the Reaction time task (simple mode) (p=0.01) and for two parameters of the Spatial working memory subtest (p=0.02 and p=0.04). At the twelve months evaluation, the change in performance compared to baseline, was also significantly different between both groups for the Attention switching task (mean latency) (p=0.04), for the Paired associates learning (p=0.03) and the third parameter of the Spatial working memory task (strategy) (p=0.02). Only the change on the Verbal memory recognition task and on one parameter of the Attention switching task (percent correct trials) did not significantly differ between the groups. The practice effect was adequately taken into account by including a control group with CI candidates (Table 1, Risk of bias B). Both the CI recipients group and the CI candidates group were assumed to be comparable. However, no statistical tests were performed to analyze whether the groups are indeed comparable. Baseline hearing thresholds appeared to be considerably lower in the CI candidates compared to the CI recipients (average baseline threshold at 0.5, 1, 2 and 4 kHz: 77.3 (±28.3) dB HL for CI candidates and 96.4 (±13.1) dB HL for CI recipients) and also the duration of hearing loss is lower in the CI candidates (mean: 24.0 (±21.8) years) compared to the CI recipients (mean: 34.4 (±18.6) years). Furthermore, parametric tests were used, without correction for multiple testing. Another limitation is that mean outcomes for each group separately were not reported, making it impossible to judge the clinical relevance of the observed significant difference between both groups (Table 1, Risk of bias C).

3.2.5. Mosnier – 2015

Mosnier, et al. (2015) were the first to systematically investigate the cognitive outcomes

after cochlear implantation in older adults with modern, multi-electrode CIs. All CI recipients entered, by default, the postactivation aural rehabilitation program, which involves speech perception tasks and semantic and cognitive tasks that engage memory, attention span, speed of processing, and mental flexibility (Table 1, Risk of bias D). Ninety-four older adults between the age of 65 and 85, without any major cognitive impairment, were enrolled in the study. The average duration of profound hearing loss at the implanted ear was 11 years (±15.1). A cognitive test battery was administered prior and at six and twelve months after surgery. The test battery consisted of the MMSE (Folstein, Folstein, & McHugh, 1975), the Five-Word Test (FWT) (Dubois et al., 2002), Clock drawing test, d2 test of attention (Brickenkamp and Zillner, 1990) and TMT part A and B (Tombaugh, 2004) (Appendix C). Written instructions were given. Yet, no additional adjustments at item level were reported (Table 1, Risk of bias A). In case of the MMSE, four points to be obtained rely on hearing, which possibly causes a slight underestimation of the preoperative performance on this test. Results on each test were classified as either normal or abnormal with respect to the normative data. Participants were categorized in two groups for each individual test, based on the preimplantation score for that test: participants with normal and participants with abnormal preoperative scores for the test (number of participants in each group varies for each test). The participants with preoperative abnormal scores showed significant improvements in all tests except for the Clock drawing test. The improvement was significant as early as six months for the MMSE (p=0.02), the FWT (p=0.004), the d2 test of attention (speed) (p=0.008), and the TMT part B (p=0.03), and became significant at twelve months for the TMT part A (p=0.02) and the number of errors on the d2 test of attention (p<0.001). The participants with normal preoperative scores remained stable over time for most tests. A significant decline was observed, however, in performance on the FWT at six and twelve months (p=0.002). Also the clock-drawing test presented a significant decline at twelve months after implantation (p=0.046). No control group was included to correct for a possible practice effect (Table 1, Risk of bias B). Parametric paired-samples t test is adequate given the large sample size and the repeated measures in the same subject. However, no correction for multiple testing is applied. Moreover, splitting the group based on measurements that are part of the outcome measurements induces regression to the mean, a statistical phenomenon (Barnett, van der Pols, & Dobson, 2005) (Table 1, Risk of bias C).

3.2.6. Sonnet – 2017

Sonnet, et al. (2017) evaluated cognition among 16 older adults with postlingual severe to profound hearing loss prior to, at six and at twelve months after unilateral implantation. The mean duration of deafness was 17 years and the mean duration of hearing aid use was approximately 15 years. The cognitive test battery comprised the Mini-Mental State Examination (MMSE) (Folstein, et al., 1975), the Rey complex figure test (Osterrieth, 1944; Rey, 1941), TMT part A and B (Tombaugh, 2004), FWT (Dubois, et al., 2002) and test de dénomination orale d'image (DO80) (Deloche and

Hannequin, 1997) (Appendix C). Sonnet, et al. (2017) stated that, for the MMSE, written instructions were provided to avoid wrong answers due to hearing loss. Additionally, in some patients, item 24 of the MMSE was removed, because this item involves the repeating of a spoken sentence. Some patients could not complete this item, possibly due to their hearing loss. Yet, the other three items of the MMSE that rely on hearing were not removed for analysis. The other tests used in the study did not rely on hearing, except for the instructions (Table 1, Risk of bias A). Overall, no significant changes were found in performance on any of these cognitive tests across the three measurements. For instance, the mean MMSE score was 27.1 (±2.1), 26.0 (±3.0) and 27.7 (±1.6) prior to, at six months and twelve months after surgery respectively. No control group was included to account for possible practice effect (Table 1, Risk of bias B). The use of parametric student's t tests for independent samples is suboptimal due to the small sample size. Moreover, given the repeated measures in the same subjects, tests for related samples would have been more appropriate (Table 1, Risk of bias C).

4. Discussion

The aim of this review was to assess the existing literature on the cognitive outcomes after cochlear implantation with a multi-electrode implant in older adults. Six pioneering articles have been found eligible, including a total of 166 CI recipients. Of the six selected articles, five reported improvements in cognition after implantation across all cognitive domains: learning and memory, language, perceptual-motor function, executive function and complex attention (Ambert-Dahan, et al., 2017; Castiglione, et al., 2016; Cosetti, et al., 2016; Jayakody, et al., 2017; Mosnier, et al., 2015). Only one study, the one by Sonnet, et al. (2017), observed no significant change in cognitive performance after implantation. However, the risk of bias appeared to be considerably high in most studies.

First of all, the suitability of the cognitive tests utilized to examine cognition among hearing-impaired subjects could not be assessed thoroughly in several studies, due to the lack of detailed information on the adaptation of verbal (sub)tests. Only for one study (Jayakody, et al., 2017) we could state with certainty that the used cognitive test battery was adequate for the hearing-impaired. In this study, a non-verbal, computerized cognitive test battery was used, the CANTAB. In another study (Ambert-Dahan, et al., 2017), the two cognitive tests (MoCA and CODEX) were reported to be adapted with visual presentation on a screen. More detailed information is missing however, which makes it difficult to evaluate the appropriateness of the adaptation. Castiglione, et al. (2016) reported that test materials were tailored for the individual according to their hearing loss and hearing treatment program, without any more detail about this tailoring. Does this mean that both the instructions and the test items that rely on hearing were presented in written format, or that just the test instructions were presented visually, or something else? In the three other studies, at least one (sub)test was not appropriate for hearing-impaired participants, based on the information obtained from

the manuscript. In general, the instructions appeared to have been adequately visually presented to the hearing-impaired subjects in all studies (except for Sonnet, et al. (2017), who did not describe this adaptation in the manuscript). Yet, in most studies at least one (sub)test was not entirely appropriate for hearing-impaired participants or for at least one (sub)test it was unclear whether the required adaptations were adequately done.

If, for instance, a verbal memory test is administered to a person with a hearing loss, this person may not perceive the to-be-remembered words and may, as a consequence, not perform at his level (Dupuis, et al., 2015). Moreover, even if the hearing-impaired person can hear the words, it may have required more effort to correctly perceive them, which leaves less cognitive resources available for the process of remembering (Pichora-Fuller et al., 2016). This, in turn, may also lead to an underestimation of the cognitive abilities of a hearing-impaired person. Since a CI improves hearing and speech perception (Clark, et al., 2012; Cosetti and Lalwani, 2015), the negative effect of the hearing loss is likely to be greater before than after implantation. Therefore, by selecting an inadequate cognitive assessment tool or by not adequately modifying an existing test, an improvement in postimplantation test score may be generated by improved hearing rather than by improved cognition.

Future studies are encouraged to make use of cognitive assessment tools suitable for the hearing-impaired population. Recently two such tools have been developed: the Repeatable Battery for the Assessment of Neuropsychological Status for Hearing-impaired individuals (RBANS-H) (Claes et al., 2016) and the Hearing-Impaired Montreal Cognitive Assessment (HI-MoCA) (V. Y. Lin et al., 2017). The RBANS-H is an adaptation of the RBANS, providing audiovisual presentation of the instructions and the test items. The HI-MoCA on the other hand, is an adaptation of the MoCA. This is a solely visual cognitive screening test.

A second risk of bias relates to the control of practice effects. Since the CI recipients were tested more than once, the test scores may be inflated due to practice effects. One study (Jayakody, et al., 2017) controlled for the practice effect by including a control group of CI candidates who were tested at the same intervals. Significant differences were observed in change of cognitive performance between the interventional and the control group. The authors assumed both groups to be similar, but the baseline hearing thresholds were considerably lower and the duration of hearing loss was substantially shorter in the control group compared to the interventional group of CI recipients. Despite these noticeable differences, no statistical tests were run to explore the similarity of both groups. As a consequence, it remains uncertain whether both groups were indeed comparable in terms of preoperative hearing capabilities and hearing status, cognition, etc. Castiglione, et al. (2016) also included a control group, consisting of normal-hearing older adults. However, this control group was only tested once and was not enrolled to control for possible practice effects. The other four studies did not include a control group (Ambert-Dahan, et al., 2017; Cosetti, et al., 2016; Mosnier, et

al., 2015). Especially the studies of Mosnier, et al. (2015) and Sonnet, et al. (2017) are susceptible for practice effects, because of the three measurements within a 1-year period.

It is important to note however, that the inclusion of a comparable control group is not at all straightforward. A randomized controlled design, in which eligible CI candidates are randomly assigned to either the interventional group or the control group, would be ideal to investigate the effect of cochlear implantation on cognition. Yet, not giving a CI to patients who do meet the criteria for cochlear implantation is far from ethical. Another way of implementing a control group, is making use of the existing waiting period for CI subsidy, as Jayakody, et al. (2017) did. Patients who are waiting for the subsidy take part in the control group and are tested at the same interval as the CI recipients. This closely resembles a delayed-start study design (D'Agostino, 2009). Although this design is superior to a cohort study, it has several limitations. The most important being the lack of long-term follow-up data. Indeed, the waiting period is limited to six up to twelve months. This makes a comparison between CI candidates and CI recipients more than one year after the baseline evaluation impossible, as the CI candidates are all CI recipients themselves by then. Enrolling patients into the control group who almost, but not yet, meet the inclusion criteria for cochlear implantation, may be another way to control for practice effects. Yet, this holds an intrinsic bias, as the control group and the interventional group are not exactly the same in terms of hearing capabilities. Nevertheless, this may yield interesting information. Another, more feasible method to minimize practice effects is the use of equivalent alternate forms of a cognitive test. However, no use of alternate forms was reported in any of the six studies, except for the verbal fluency test in Mosnier, et al. (2015). However, this test was eventually excluded from the analyses, exactly because of the different normative data for each version, which made comparison of the scores impossible.

The statistical methods involve a third risk of bias. First of all, two studies (Ambert-Dahan, et al., 2017; Cosetti, et al., 2016) did not perform statistical analyses to investigate the change in cognition after cochlear implantation. They only described the results qualitatively. It is therefore not possible to decide whether the observed improvements in cognition are significant, or simply resemble variation by nature and other confounding effects, such as practice effects. All other studies performed parametric analyses, although this was only appropriate in the study of Mosnier, et al. (2015). To be precise, the sample sizes of the other three studies were too small to use parametric tests (Castiglione, et al., 2016; Jayakody, et al., 2017; Sonnet, et al., 2017). In two studies (Jayakody, et al., 2017; Mosnier, et al., 2015), correction for multiple testing was required, but not applied. Furthermore, Jayakody, et al. (2017) reported significant differences in the *change* in performance between the CI recipients and the CI candidates. However, descriptive data of the cognitive variables (e.g. the mean and standard deviation before and after implantation for each group) were not reported, making it impossible to compare the performance of both groups at the start and end point and to estimate the clinical relevance of these significant differences between the

evolution of both groups. Finally, Mosnier, et al. (2015) split the sample of 94 CI recipients into two subgroups based on preoperative measurements for each individual test: one group with normal preoperative results for the given test, and one group with abnormal preoperative results for that test. Categorizing the participants into groups based on their baseline measurements compounds the effect of regression to the mean (Barnett, et al., 2005). This statistical phenomenon happens because measurements are observed with random error. Consequently, unusually poor or superior performances tend to be followed by performances that are closer to the mean. This can make natural variation in repeated data look like real change or can make the real change being overestimated. For instance, for the Five-word test in the study by Mosnier, et al. (2015) a significant increased performance was demonstrated in the preoperatively poorest performing group and a significant declined performance in the preoperatively best performing group. Considering the effect of regression to the mean, it is fairly well possible that one analysis for the whole group ended up in stable results. Analogously for the other tests, the observed change in the preoperatively poorest performing group is likely to be affected by regression to the mean.

Other sources of bias are the large number of missing data in the study of Cosetti, et al. (2016) and the postoperative auditory-cognitive rehabilitation program in the studies of Ambert-Dahan, et al. (2017) and Mosnier, et al. (2015). This program is an integral part of the clinical practice involving cochlear implantation. It focuses on optimizing speech perception with the CI speech processor and improving cognitive abilities required for communication. It is not improbable that this program has a direct positive influence on cognitive performance (Martin, Clare, Altgassen, Cameron, & Zehnder, 2011; Sharma, Srivastava, Kumar, & Sharma, 2016; Verhaeghen, Marcoen, & Goossens, 1992). Furthermore, the follow-up period of all studies is rather short, ranging from 1 year (in all but one study) to 3.7 year (Cosetti, et al., 2016). As age-related cognitive decline progresses gradually, a longer follow-up period is essential to understand the cognitive evolution after cochlear implantation in older adults.

In Figure 1, three hypotheses are presented with regard to the cognitive outcomes after cochlear implantation. The results, as reported by the authors of the six selected articles, best match the third hypothesis, in which an increase in cognition and an age-appropriate speed of decline is induced by the cochlear implantation. However, after critically reviewing these studies, the risk of bias is found to be high in most studies. Detailed information on the adaptation of the cognitive tests for hearing-impaired subjects is frequently lacking, practice effects are not taken into account in most studies and statistical analyses are missing or suboptimal. One study appears to stand out, in that it made use of a clearly defined non-verbal cognitive test battery and that it enrolled a control group. However, even in this study the statistical data are incomplete and the sample size is too small to provide conclusive evidence of an increase in cognitive outcomes after cochlear implantation in older adults. More, well-designed studies with long follow-up periods are, therefore, imperative to verify whether (and how) cochlear implantation influences cognition in older adults.

5. Conclusion

Although five out of six studies investigating the cognitive outcomes after cochlear implantation in older adults reported improved cognition after implantation across a variety of cognitive domains, the results were exposed to several risks of bias and are, therefore, considered inconclusive. By highlighting the limitations of the existing literature, this reviews aims to stimulate new research to (1) use appropriate cognitive assessment tools in hearing-impaired individuals and, if applicable, to describe the modifications in detail, (2) to attempt to control for practice effects, for instance by using alternate forms of a test, and (3) to perform appropriate statistical tests, given the characteristics of the sample, and to report both the outcomes of the statistical tests and the descriptive values (e.g. mean and standard deviation).

6. References

Acar, B., Yurekli, M. F., Babademez, M. A., Karabulut, H., & Karasen, R. M. (2011). Effects of hearing aids on cognitive functions and depressive signs in elderly people. *Archives of Gerontology & Geriatrics, 52*(3), pp. 250-252. doi:http://dx.doi.org/10.1016/j.archger.2010.04.013

Ambert-Dahan, E., Routier, S., Marot, L., Bouccara, D., Sterkers, O., Ferrary, E., & Mosnier, I. (2017). Cognitive Evaluation of Cochlear Implanted Adults Using CODEX and MoCA Screening Tests. *Otology & Neurotology, 38*(8), pp. e282-e284. doi:10.1097/MAO.0000000000001464

Amieva, H., Ouvrard, C., Giulioli, C., Meillon, C., Rullier, L., & Dartigues, J. F. (2015). Self-Reported Hearing Loss, Hearing Aids, and Cognitive Decline in Elderly Adults: A 25-Year Study. *J Am Geriatr Soc, 63*(10), pp. 2099-2104. doi:10.1111/jgs.13649

Aplin, D. Y. (1993). Psychological assessment of multi-channel cochlear implant patients. *J Laryngol Otol, 107*(4), pp. 298-304.

Barnett, A. G., van der Pols, J. C., & Dobson, A. J. (2005). Regression to the mean: what it is and how to deal with it. *Int J Epidemiol, 34*(1), pp. 215-220. doi:10.1093/ije/dyh299

Belmin, J., Pariel-Madjlessi, S., Surun, P., Bentot, C., Feteanu, D., Lefebvre des Noettes, V., . . . Golmard, J. L. (2007). The cognitive disorders examination (Codex) is a reliable 3-minute test for detection of dementia in the elderly (validation study on 323 subjects). *Presse Med, 36*(9 Pt 1), pp. 1183-1190. doi:10.1016/j.lpm.2007.03.016

Brickenkamp, R., & Zillner, E. (1990). *The d2 test of attention* Seatlle, WA: Hogrefe & Huber Publishers.

Cambridge Cognition Ltd. (2012). *CANTABeclipse test administration guide* Cambridge: England.

Capretta, N. R., & Moberly, A. C. (2016). Does quality of life depend on speech recognition performance for adult cochlear implant users? *Laryngoscope, 126*(3), pp. 699-706. doi:10.1002/lary.25525

Castiglione, A., Benatti, A., Girasoli, L., Caserta, E., Montino, S., Pagliaro, M., . . . Martini, A. (2015). Cochlear implantation outcomes in older adults. *Hearing, Balance and Communication, 2015, Vol.13(2), p.86-88, 13*(2), pp. 86-88. doi:10.3109/13625187.2015.1030885

Castiglione, A., Benatti, A., Velardita, C., Favaro, D., Padoan, E., Severi, D., . . . Martini, A. (2016). Aging, Cognitive Decline and Hearing Loss: Effects of Auditory Rehabilitation and Training with Hearing Aids and Cochlear Implants on Cognitive Function and Depression among Older Adults. *Audiol Neurootol, 21 Suppl 1*, pp. 21-28. doi:10.1159/000448350

Choi, A. Y., Shim, H. J., Lee, S. H., Yoon, S. W., & Joo, E. J. (2011). Is cognitive function in adults with hearing impairment improved by the use of hearing aids? *Clin Exp Otorhinolaryngol, 4*(2), pp. 72-76. doi:10.3342/ceo.2011.4.2.72

Claes, A. J., de Backer, S., Van de Heyning, P., Gilles, A., Van Rompaey, V., & Mertens, G. (2018). Postoperative cognitive dysfunction after cochlear implantation. *Eur Arch Otorhinolaryngol* doi:10.1007/s00405-018-4976-6

Claes, A. J., Mertens, G., Gilles, A., Hofkens-Van den Brandt, A., Fransen, E., Van Rompaey, V., & Van de Heyning, P. (2016). The Repeatable Battery for the Assessment of Neuropsychological Status for Hearing Impaired Individuals (RBANS-H) before and after Cochlear Implantation: A Protocol for a Prospective, Longitudinal Cohort Study. *Front Neurosci, 10*, p 512. doi:10.3389/fnins.2016.00512

Clark, J. H., Yeagle, J., Arbaje, A. I., Lin, F. R., Niparko, J. K., & Francis, H. W. (2012). Cochlear implant rehabilitation in older adults: literature review and proposal of a conceptual framework. *J Am Geriatr Soc, 60*(10), pp. 1936-1945. doi:10.1111/j.1532-5415.2012.04150.x

Cosetti, M. K., & Lalwani, A. K. (2015). Is cochlear implantation safe and effective in the elderly? *Laryngoscope, 125*(6), pp. 1279-1281. doi:10.1002/lary.25055

Cosetti, M. K., Pinkston, J. B., Flores, J. M., Friedmann, D. R., Jones, C. B., Roland, J. T., Jr., & Waltzman, S. B. (2016). Neurocognitive testing and cochlear implantation: insights into performance in older adults. *Clinical Interventions In Aging, 11*, pp. 603-613. doi:10.2147/CIA.S100255

Crary, W. G., Wexler, M., Berliner, K. I., & Miller, L. W. (1982). Psychometric studies and clinical interviews with cochlear implant patients. *Ann Otol Rhinol Laryngol Suppl, 91*(2 Pt 3), pp. 55-58.

D'Agostino, R. B., Sr. (2009). The delayed-start study design. *N Engl J Med, 361*(13), pp. 1304-1306. doi:10.1056/NEJMsm0904209

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., . . . Munro, K. J. (2015). Hearing loss and cognition: the role of hearing aids, social isolation and depression. *PLoS ONE, 10*(3), p e0119616. doi:http://dx.doi.org/10.1371/journal.pone.0119616

Deloche, G., & Hannequin, D. (1997). *Test de dénomination orale d'images (DO-80)* Paris: Centre de Psychologie Appliquée.

Dubois, B., Touchon, J., Portet, F., Ousset, P. J., Vellas, B., & Michel, B. (2002). "The 5 words": a simple and sensitive test for the diagnosis of Alzheimer's disease. *Presse Med, 31*(36), pp. 1696-1699.

Dupuis, K., Pichora-Fuller, M. K., Chasteen, A. L., Marchuk, V., Singh, G., & Smith, S. L. (2015). Effects of hearing and vision impairments on the Montreal Cognitive Assessment. *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn, 22*(4), pp. 413-437. doi:10.1080/13825585.2014.968084

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res, 12*(3), pp. 189-198.

Gallacher, J., Ilubaera, V., Ben-Shlomo, Y., Bayer, A., Fish, M., Babisch, W., & Elwood, P. (2012). Auditory threshold, phonologic demand, and incident dementia. *Neurology, 79*(15), pp. 1583-1590. doi:10.1212/WNL.0b013e31826e263d

Gantz, B. J., Woodworth, G. G., Knutson, J. F., Abbas, P. J., & Tyler, R. S. (1993). Multivariate predictors of audiological success with multichannel cochlear implants. *Annals of Otology, Rhinology & Laryngology, 102*(12), pp. 909-916. doi:10.1177/000348949310201201

Heydebrand, G., Hale, S., Potts, L., Gotter, B., & Skinner, M. (2007). Cognitive predictors of improvements in adults' spoken word recognition six months after cochlear implant activation. [Research Support, N.I.H., Extramural]. *Audiology & Neuro-Otology, 12*(4), pp. 254-264.

Hogan, A. (1997). Implant outcomes: towards a mixed methodology for evaluating the efficacy of adult cochlear implant programmes. *Disability & Rehabilitation, 19*(6), pp. 235-243.

Holden, L. K., Finley, C. C., Firszt, J. B., Holden, T. A., Brenner, C., Potts, L. G., . . . Skinner, M. W. (2013). Factors affecting open-set word recognition in adults with cochlear implants. [Research Support, N.I.H., Extramural]. *Ear & Hearing, 34*(3), pp. 342-360. doi:http://dx.doi.org/10.1097/AUD.0b013e3182741aa7

Huber, M., & Kaiser, A. (2017). Re.: The Paper "Impact of Cochlear Implantation on Cognitive Functions of Older Adults: Pilot Test Results," Recently Published in Otology & Neurotology (38: E289-E295_2017). *Otology & Neurotology*doi:10.1097/MAO.0000000000001654

Jayakody, D. M. P., Friedland, P. L., Nel, E., Martins, R. N., Atlas, M. D., & Sohrabi, H. R. (2017). Impact of Cochlear Implantation on Cognitive Functions of Older Adults: Pilot Test Results. *Otology & Neurotology, 38*(8), pp. e289-e295. doi:10.1097/MAO.0000000000001502

Kaplan, E., Goodglass, H., & Weintraub, S. (1983). *Boston naming test* Philadelphia: Lea & Febiger.

Knopke, S., & Olze, H. (2017). Hearing rehabilitation with cochlear implants and cognitive abilities. *HNO*doi:10.1007/s00106-017-0423-z

Knutson, J. F., Hinrichs, J. V., Tyler, R. S., Gantz, B. J., Schartz, H. A., & Woodworth, G. (1991). Psychological predictors of audiological outcomes of multichannel cochlear implants: preliminary findings. *Annals of Otology, Rhinology & Laryngology, 100*(10), pp. 817-822. doi:10.1177/000348949110001006

Kropp, P., Niederberger, U., & Gerber, W. D. (2000). Prediction of verbal and numerical comprehension in patients with cochlear implants. *Laryngo- Rhino-Otologie, 79*(7), pp. 388-391.

Li, L., Blake, C., Sung, Y., Shpritz, B., Chen, D., Genther, D. J., . . . Lin, F. R. (2017). The Studying Multiple Outcomes After Aural Rehabilitative Treatment Study: Study Design and Baseline Results. *Gerontol Geriatr Med, 3*, p 2333721417704947. doi:10.1177/2333721417704947

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gotzsche, P. C., Ioannidis, J. P., . . . Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ, 339*, p b2700. doi:10.1136/bmj.b2700

Lin, F. R., Metter, E. J., O'Brien, R. J., Resnick, S. M., Zonderman, A. B., & Ferrucci, L. (2011). Hearing loss and incident dementia. *Archives of Neurology, 68*(2), pp. 214-220. doi:http://dx.doi.org/10.1001/archneurol.2010.362

Lin, F. R., Yaffe, K., Xia, J., Xue, Q. L., Harris, T. B., Purchase-Helzner, E., . . . Health, A. B. C. S. G. (2013). Hearing loss and cognitive decline among older adults.*JAMA Internal Medicine, 173*(4), pp. 293-299. doi:http://dx.doi.org/10.1001/jamainternmed.2013.1868

Lin, V. Y., Chung, J., Callahan, B. L., Smith, L., Gritters, N., Chen, J. M., . . . Masellis, M. (2017). Development of cognitive screening test for the severely hearing impaired: Hearing-impaired MoCA. *Laryngoscope, 127 Suppl 1*, pp. S4-S11. doi:10.1002/lary.26590

Martin, M., Clare, L., Altgassen, A. M., Cameron, M. H., & Zehnder, F. (2011). Cognition-based interventions for healthy older people and people with mild cognitive impairment. *Cochrane Database Syst Rev*(1), p CD006220. doi:10.1002/14651858.CD006220.pub2

Miller, G., Miller, C., Marrone, N., Howe, C., Fain, M., & Jacob, A. (2015). The impact of cochlear implantation on cognition in older adults: a systematic review of clinical evidence. *BMC Geriatr, 15*, p 16. doi:10.1186/s12877-015-0014-3

Mosnier, I., Bebear, J. P., Marx, M., Fraysse, B., Truy, E., Lina-Granade, G., . . . Sterkers, O. (2015). Improvement of cognitive function after cochlear implantation in elderly patients. [Research Support, Non-U.S. Gov't]. *JAMA Otolaryngology-- Head & Neck Surgery, 141*(5), pp. 442-450. doi:http://dx.doi.org/10.1001/jamaoto.2015.129

Nasreddine, Z. S., Phillips, N. A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., . . . Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc, 53*(4), pp. 695-699. doi:10.1111/j.1532-5415.2005.53221.x

Osterrieth, P. A. (1944). Le test de copie d'une figure complexe: Contribution à l'étude de la perception et de la mémoire. [Test of copying a complex figure: Contribution to the study of perception and memory]. *Archives de Psychologie, 30*, pp. 206-356.

Parkin, J. L., Stewart, B. E., Dankowski, K., & Haas, L. J. (1989). Prognosticating speech performance in multichannel cochlear implant patients. *Otolaryngol Head Neck Surg, 101*(3), pp. 314-319. doi:10.1177/019459988910100304

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., . . . Wingfield, A. (2016). Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL). *Ear & Hearing, 37 Suppl 1*, pp. 5S-27S. doi:10.1097/AUD.0000000000000312

Randolph, C. (1998). *RBANS update: Repeatable Battery for the Assessment of Neuropsychological Status* (second ed.) Bloomington: Pearson.

Rey, A. (1941). L'examen psychologique dans les cas d'encéphalopathie traumatique (Les problèmes). [The psychological examination in cases of traumatic encephalopathy (Problems)]. *Archives de Psychologie, 28*, pp. 215-285.

Sachdev, P. S., Blacker, D., Blazer, D. G., Ganguli, M., Jeste, D. V., Paulsen, J. S., & Petersen, R. C. (2014). Classifying neurocognitive disorders: the DSM-5 approach. *Nat Rev Neurol, 10*(11), pp. 634-642. doi:10.1038/nrneurol.2014.181

Sharma, I., Srivastava, J., Kumar, A., & Sharma, R. (2016). Cognitive remediation therapy for older adults. *Journal of Geriatric Mental Health, 3*(1), pp. 57-65. doi:10.4103/2348-9995.181919

Shipp, D., Nedzelski, J., Chen, J., & Hanusaik, L. (1997). Prognostic indicators of speech recognition performance in postlinguistically deafened adult cochlear implant users. *Adv Otorhinolaryngol, 52*, pp. 74-77.

Sonnet, M. H., Montaut-Verient, B., Niemier, J. Y., Hoen, M., Ribeyre, L., & Parietti-Winkler, C. (2017). Cognitive Abilities and Quality of Life After Cochlear Implantation in the Elderly. *Otology & Neurotology, 38*(8), pp. e296-e301. doi:10.1097/MAO.0000000000001503

Summerfield, A. Q., & Marshall, D. H. (1995). Preoperative predictors of outcomes from cochlear implantation in adults: performance and quality of life. *Ann Otol Rhinol Laryngol Suppl, 166*, pp. 105-108.

Tombaugh, T. N. (2004). Trail Making Test A and B: normative data stratified by age and education. *Archives of Clinical Neuropsychology, 19*(2), pp. 203-214. doi:10.1016/S0887-6177(03)00039-8

Valentijn, S. A., van Boxtel, M. P., van Hooren, S. A., Bosma, H., Beckers, H. J., Ponds, R. W., & Jolles, J. (2005). Change in sensory functioning predicts change in cognitive functioning: results from a 6-year follow-up in the maastricht aging study. [Research Support, Non-U.S. Gov't]. *Journal of the American Geriatrics Society, 53*(3), pp. 374-380.

van Dijk, J. E., van Olphen, A. F., Langereis, M. C., Mens, L. H., Brokx, J. P., & Smoorenburg, G. F. (1999). Predictors of cochlear implant performance. *Audiology, 38*(2), pp. 109-116.

van Hooren, S. A., Anteunis, L. J., Valentijn, S. A., Bosma, H., Ponds, R. W., Jolles, J., & van Boxtel, M. P. (2005). Does cognitive function in older adults with hearing impairment improve by hearing aid use?. *International Journal of Audiology, 44*(5), pp. 265-271.

Verhaeghen, P., Marcoen, A., & Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychology & Aging, 7*(2), pp. 242-251.

Wechsler, D. (1997). *WASI-III: Wechsler Abbreviated Scale of Intelligence* San Antonia, TX: Harcourt Brace.

Appendix A

The following search string was used in the MEDLINE (PubMed) database:

> ("Cognitive Aging"[Mesh] OR "Aging"[Mesh] OR "Aged"[Mesh] OR "Geriatrics"[Mesh] OR elder[Text Word] OR elderly[Text Word] OR elders[Text Word] OR old[Text Word] OR older[Text Word] OR aged[Text Word] OR aging[Text Word] OR ageing[Text Word] OR senior[Text Word] OR seniors[Text Word] OR geriatric[Text Word] OR geriatrics[Text Word]) AND ("Cognition"[Mesh] OR "Cognition Disorders"[Mesh] OR "Dementia"[Mesh] OR "mental processes"[Mesh] OR cognit*[Text Word] OR memor*[Text Word] OR attent*[Text Word] OR dement*[Text Word] OR mental[Text Word]) AND ("Cochlear Implants"[Mesh] OR "Cochlear Implantation"[Mesh] OR (cochlear implant*))

Appendix B

The following search string was used in the Cochrane Library database:

> (cochlear NEXT implant*) AND (cognitive OR cognition OR cogniti*) AND (old* OR adult OR aging OR aged OR senior OR elder* OR elderly)

Appendix C

The **COgnitive Disorders Examination (CODEX)** (Belmin, et al., 2007) is a three-minute test, which consists of three tasks: a clock drawing task, short-term memory word recall and spatiotemporal orientation. Performance is categorized into four categories: A, B, C en D, corresponding to a very low, low, high and very high risk of developing dementia respectively.

The **Montreal Cognitive Assessment (MoCA)** (Nasreddine, et al., 2005) is a one-page 30-point screening tool for mild cognitive impairment. It is administered in 10 to 15 minutes and assesses short-term memory, visuospatial abilities, executive functions, phonemic fluency, verbal abstraction, attention, concentration, working memory, language and orientation to time and place.

The **Wechsler Abbreviated Scale of Intelligence (WASI)** (Wechsler, 1997) comprises four subtests, two of which assessing language related abilities (Vocabulary and Similarities) and two assessing visuospatial and constructional abilities (Block design and Matrix reasoning).

The **Trail Making Test (TMT)** (Tombaugh, 2004) is a paper-and-pencil task in which 25 circles are distributed over a sheet of paper. In part A, the circles are numbered 1 to 25 and the participant is asked to connect the circles in ascending order. In part B, the

circles include both numbers and letters and the participant should connect the numbers and letters alternatively and in ascending order (1-A-2-B-3-C etc.).

The **controlled oral word association test** is a semantic and phonemic verbal fluency test. The participant has to name as many exemplars of a given semantic category (animals) or as many words beginning with a given letter (F – A – S) within one minute.

The **Boston naming test** (Kaplan, et al., 1983) is a naming test comprising 60 line drawings of objects of graded difficulty, ranging from very common objects to less familiar objects.

The **Repeatable Battery for the Assessment of Neuropsychological Status (RBANS)** (Randolph, 1998) consists of twelve subtests, assessing five cognitive domains: List learning and Story memory (Immediate memory domain), Figure copy (i.e. Complex figure) and Line orientation (Visuospatial/constructional domain), Picture naming and Semantic fluency (Language domain), Digit span (i.e. Digits forward) and Coding (Attention domain), List recall, List recognition, Story recall and figure recall (i.e. Visual memory) (Delayed memory domain). The Picture naming subtest was not administered in the study of Cosetti, et al. (2016).

The **Cambridge Neuropsychological Test Automated Battery (CANTAB)** (Cambridge Cognition Ltd., 2012) is a nonverbal, computerized cognitive test battery (http://www.cambridgecognition.com/cantab). Six subtests were used in the study of Jayakody, et al. (2017). The Attention switching task provides a measure of cued attentional set shifting. In the Delayed matching to sample subtest a complex visual pattern is shown, followed by four similar patterns, after a delay of 0, 4 or 12 seconds. The pattern that exactly matches the target must be selected. The Paired associates learning task involves memorizing the location of specific visual patterns, whereas the Verbal recognition memory task involves memorizing twelve words under free recall and forced recognition. In the Reaction time subtest one (for the simple mode) or five (for the five-choice mode) circles are presented at the top of the screen. The participant must select the circle in which a yellow dot appears as fast as possible. The last subtest is Spatial working memory, which measures the retention and manipulation of visuospatial information.

The **Mini-Mental State Examination (MMSE)** (Folstein, et al., 1975) is a brief quantitative assessment of cognitive function. It takes approximately 10 minutes to administer and provides a total score ranging from 0 (impaired) to 30 (normal). Various cognitive domains are assessed: short-term memory, orientation to time and place, attention and calculation, naming, repetition, language and visual construction.

The **Five-Word Test (FWT)** (Dubois, et al., 2002) is a verbal memory test in which a

list of five words written on a sheet is given to the participant. He or she has to read the words out loud and try to memorize them. Four basic scores, namely free and cued immediate recall and free and cued delayed recall (after two to five minutes), are calculated and summed to obtain the total score.

In the **Clock drawing task**, the subject is asked to draw, in a circle, all the numbers as a clock face, and to set the two hands indicating twenty minutes to four.

The **d2 test of attention** (Brickenkamp and Zillner, 1990) consists of 14 lines with 47 characters each for a total of 658 items. The items are composed of the letters d and p with one, two, three or four dashes arranged either individually or in pairs above and below the letter. The participant is given 20 seconds to scan each line and mark all d with two dashes.

In the **Rey complex figure test** (Osterrieth, 1944; Rey, 1941) the participant is asked to reproduce a complicated line drawing. First the participant has to make a copy, while the figure remains on display, and after a certain interval he or she has to redraw it from memory. In the last part of the test the participant has to recognize the correct drawing from several similar exemplars.

The **test de dénomination orale d'image (DO80)** (Deloche and Hannequin, 1997) is a picture naming test, including 80 items.

Table 1. Participant characteristics and risk of bias for the individual studies. ✓ information reported. o information not reported. N/A not applicable. + no risk of bias. – high risk of bias. +/- moderate risk of bias. 6m six months. 12m twelve months. CI cand. cochlear implant candidate. CI recip. cochlear implant recipient. HI hearing-impaired. NH normal-hearing.

		1 **Ambert-Dahan – 2017**	**2** **Castiglione – 2016**		**3** **Cosetti – 2016**	**4** **Jayakody – 2017**				**5** **Mosnier – 2015**	**6** **Sonnet – 2017**
			CI recip.	**NH control**		**6m after baseline**		**12m after baseline**			
						CI recip.	**CI cand.**	**CI recip.**	**CI cand.**		
PARTICIPANT CHARACTERISTICS	n	18	15	20	7	16	23	11	11	94	16
	Male Female n (%)	11 (61.1%) 7 (38.9%)	8 (53.3%) 7 (46.7%)	9 (45%) 11 (55%)	0 (0%) 7 (100%)	7 (43.8%) 9 (56.3%)	8 (34.8%) 15 (65.2%)	6 (54.5%) 5 (45.5%)	6 (54.5%) 5 (45.5%)	45 (47.9%) 49 (52.1%)	6 (37.5%) 10 (62.5%)
	Age (year) mean (±SD)	64 (±3.5) (range: 23-83)	median: 71 (range: 67-75)	median: 70 (range: 65-80)	73.6 (±5.82) (range: 67-81)	61.8 (±15.6)	69.0 (±12.4)	67.3 (±15.9)	72.2 (±8.3)	72 (±5.0) (range: 65-85)	72.5 (±5.3) (range: 65-80)
	Duration of deafness	✓	o	N/A	✓	✓	✓	✓	✓	✓	✓
	Duration of HA use	o	o	N/A	o	o	o	o	o	✓	✓
	Number of uni-/bilateral CI	✓	o	N/A	✓	o	o	o	o	✓	✓
	Side of implantation	o	o	N/A	✓	o	o	o	o	o	o
	Level of education	o	o	o	✓	o	o	o	o	✓	o
RISK OF BIAS	(A) Suitability of cognitive test for HI?	+?	+?		+/–	+				+/–	+/–
	(B) Control of practice effect?	–	–		–	+				–	–
	(C) Statistical methods?	–	+/–		–	+/–				+/–	+/–
	(D) Other sources of bias?	auditory-cognitive rehabilitation	N/A		many missing data	N/A				auditory-cognitive rehabilitation	N/A

Table 2. Cognitive tests and outcomes for each study. In the 'outcomes' column, light grey shading indicates improvement, no shading indicates no change and dark grey shading indicates deterioration. In the last column ('specific adaptation of the test for hearing-impaired subjects?'), dark grey shading indicates that adjustments to the test are required but not reported, whereas no shading indicates that adjustments were not needed, or were adequately performed and reported. 6m six months. 12m twelve months. CDT Clock drawing test. CODEX COgnitive Disorders Examination. FWT five word test. MMSE Mini-Mental State Examination. MoCA Montreal Cognitive Assessment. Pre-CI preoperatively. Post-CI postoperatively. RBANS Repeatable Battery for the Assessment of Neuropsychological Status. TMT Trail making test. WASI Wechsler Abbreviated Scale of Intelligence.

COGNITIVE DOMAINS	COGNITIVE TESTS	OUTCOMES	SPECIFIC ADAPTATION OF THE TEST FOR HEARING-IMPAIRED SUBJECTS?
Learning and memory	RBANS – List learning[3]	[3] On average, pronounced improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments were reported, although these are needed to avoid underestimating the cognitive performance of a hearing-impaired individual.
	RBANS – Story memory[3]	[3] On average, pronounced improvement (qualitative analyses).	
	RBANS – List recall[3]	[3] On average, moderate improvement (qualitative analyses).	
	RBANS – List recognition[3]	[3] On average, pronounced improvement (qualitative analyses).	
	RBANS – Story recall[3]	[3] On average, moderate improvement (qualitative analyses).	
	CANTAB – Verbal recognition memory[4]	[4] No significant change in free recall score, immediate recognition score or delayed recognition score among CI recipients, compared to CI candidates, neither at 6 or 12m post-CI.	[4] Use of nonverbal test battery of cognitive function (words presented visually on a computer screen).
	Five-Word Test (FWT)[5,6]	[5] Significant improvements at 6 and 12m post-CI (p=0.004 and p<0.001, resp.), among patients with abnormal pre-CI FWT scores. Significant decline at 6 and 12m post-CI (p=0.002 and p=0.002, resp.), among patients with normal pre-CI FWT scores.	[5] Instructions presented visually. Test items are presented in written format in this test (originally, no adjustments needed).
		[6] No significant change.	[6] No test adjustments were reported. If patients understood the

			instructions, no additional adjustments were required, as the test items are presented in written format in this test.
Language	WASI – Vocabulary[3]	[3] On average, minimal improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
	WASI – Similarities[3]	[3] On average, minimal decline (qualitative analyses).	
	Boston naming test[3]	[3] On average, minimal improvement (qualitative analyses).	
	Verbal fluency test (semantic)[3,5]	[3] On average, moderate improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
		[5] No comparison between pre-CI and post-CI evaluation possible, due to changed lists of words (animals, vegetables and furniture).	[5] Written instructions were given. No additional test adjustments required.
	Verbal fluency test (phonemic)[3,5]	[3] On average, no change (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
		[5] No comparison between pre-CI and post-CI evaluation possible, due to changed letters (P, R and V).	[5] Written instructions were given. No additional test adjustments required.
	Test de dénomiation orale d'image (DO80)[6]	[6] No significant change.	[6] No test adjustments were reported. If patients understood the instructions, no additional adjustments were required.
Perceptual-motor function	WASI – Block design[3]	[3] On average, moderate improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments were required.
	WASI – Matrix reasoning[3]	[3] On average, moderate improvement (qualitative analyses).	
	RBANS – Figure copy[3]	[3] On average, pronounced decline (qualitative analyses).	
	RBANS – Line orientation[3]	[3] On average, minimal improvement (qualitative analyses).	
	RBANS – Figure recall[3]	[3] On average, moderate decline (qualitative analyses).	
	CANTAB – Delayed matching to sample[4]	[4] No significant change among CI recipients, compared to CI candidates, neither at 6 or 12m post-CI.	[4] Use of nonverbal test battery of cognitive function (words presented visually on a computer screen).

	CANTAB – Paired-associate learning[4]	[4] Significant improvement 12m post-CI (p=0.03) in total errors among CI recipients, compared to CI candidates.	[4] Use of nonverbal test battery of cognitive function (words presented visually on a computer screen).
	CANTAB – Spatial working memory[4]	[4] Changes between baseline (pre-CI/baseline) and both 6m and 12m later were significantly different between CI recipients and CI candidates for between errors (p=0.02 at 6m and p=0.03 at 12m) and for between errors four to eight boxes (p=0.04 at 6m and p=0.05 at 12m). CI recipients performed significantly better. Strategy use improved significantly 12m post-CI among CI recipients, compared to CI candidates (p=0.02).	[4] Use of nonverbal test battery of cognitive function (words presented visually on a computer screen).
	Rey complex figure test[6]	[6] No significant change.	[6] No test adjustments were reported. If patients understood the instructions, no additional adjustments were required.
Executive function	RBANS – Digit span[3]	[3] On average, minimal improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments were reported, although these are needed to avoid underestimating the cognitive performance of a hearing-impaired individual.
	Trail making test (TMT) A[3,5,6]	[3] On average, moderate decline (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
		[5] Significant improvement at 12m post-CI (p=0.02) among patients with abnormal pre-CI TMT A scores. No significant change in patients with normal pre-CI TMT A scores.	[5] Written instructions were given. No additional test adjustments required.
		[6] No significant change.	[6] No test adjustments were reported. If patients understood the instructions, no additional adjustments were required.
	Trail making test (TMT) B[3,5,6]	[3] On average, moderate decline (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
		[5] Significant improvements at 6 and 12m post-CI (p=0.03 and p=0.03, resp.) among patients with abnormal pre-CI TMT B scores. No significant change in patients with normal pre-CI TMT B scores.	[5] Written instructions were given. No additional test adjustments required.

		[6] No significant change	[6] No test adjustments were reported. If patients understood the instructions, no additional adjustments were required.
	CANTAB – Attention switching task[4]	[4] Significant improvement 12m post-CI (p=0.04) in latency among CI recipients, compared to CI candidates. No significant change in percent correct among CI recipients, compared to CI candidates, neither at 6 or 12m post-CI.	[4] Use of nonverbal test battery of cognitive function.
	Clock drawing test (CDT)[5]	[5] No significant change in patients with abnormal pre-CI CDT scores. Significant deterioration at 12m post-CI (p=0.046) in patients with normal pre-CI CDT scores.	[5] Written instructions were given. No additional test adjustments required.
Complex attention	RBANS – Coding[3]	[3] On average, pronounced improvement (qualitative analyses).	[3] Pre-CI, instructions were given in oral and written format. No additional test adjustments required.
	CANTAB – Reaction time (simple)[4]	[4] Changes between baseline (pre-CI/baseline) and both 6m and 12m later were significantly different between CI recipients and CI candidates (p=0.01 at 6m and p=0.03 at 12m). CI recipients performed significantly better.	[4] Use of nonverbal test battery of cognitive function.
	CANTAB – Reaction time (five-choice)[4]	[4] No significant change among CI recipients, compared to CI candidates, neither at 6 or 12m post-CI.	[4] Use of nonverbal test battery of cognitive function.
	d2 test of attention[5]	[5] Significant improvements in speed at 6 and 12m post-CI (p=0.008 and p<0.001, resp.) and significant improvement in number of errors at 12m post-CI (p<0.001) among patients with abnormal pre-CI d2 scores. No significant change in patients with normal pre-CI d2 scores.	[5] Written instructions were given. No additional test adjustments required.
Overall cognition	CODEX[1]	[1] 2/4 patients with abnormal pre-CI CODEX score, obtained normal post-CI score (no statistical analyses).	[1] CODEX was adapted with visual presentation on a screen (no more information).
	MoCA[1,2]	[1] 4/8 patients with abnormal pre-CI MoCA score, obtained normal post-CI score (no statistical analyses).	[1] MoCA was adapted with visual presentation on a screen (no more information).

		[2] Significant improvement (p<0.01).	[2] Test materials were tailored for the individual according to their hearing loss and hearing treatment program (no more information).
	MMSE[5,6]	[5] Significant improvements at 6 and 12m post-CI (p=0.02 and p=0.01, resp.) among patients with abnormal pre-CI MMSE scores. No significant change in patients with normal pre-CI MMSE scores.	[5] Written instructions were given. No additional test adjustments were reported, although these are needed to avoid underestimating the cognitive performance of a hearing-impaired individual.
		[6] No significant change (on average: decrease at 6m, increase at 12m post-CI).	[6] Written instructions were provided. Item 24 (repeating a sentence) removed in some patients. No additional adjustment reported.

[1](Ambert-Dahan, et al., 2017)
[2](Castiglione, et al., 2016)
[3](Cosetti, et al., 2016)
[4](Jayakody, et al., 2017)
[5](Mosnier, et al., 2015)
[6](Sonnet, et al., 2017)