THE RELATIONSHIP BETWEEN HEARING IMPAIRMENT AND COGNITIVE FUNCTION: A META-ANALYSIS IN ADULTS

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ABSTRACT

Background: Hearing loss affects over 1.23 billion people globally. It has been proposed that hearing impairment negatively impacts on cognition. Some studies have demonstrated a faster rate of decline in cognition, and increased risk of incident all-cause dementia. This finding is not ubiquitous. This study used meta-analysis to examine the evidence-base regarding the relationship between hearing and cognition.

Objective and type of review: Meta-analyses examined evidence for and against seven questions. Is cognition poorer in individuals with normal hearing compared to (i) untreated or (ii) treated hearing impairment, is cognition associated with degree of hearing impairment in (iii) untreated and/or, (iv) treated hearing, is cognition (v) different in untreated compared to treated hearing impairment, (vii) does cognition improve after intervention, and (vii) how is hearing impairment differentially associated with cognitive ability across six domains of cognition?

Search and evaluation strategy: Published and grey literature was reviewed. Papers were included if they studied the relationship between hearing and cognition in adults with and without hearing impairment.

Results: The 33 included studies contributed 40 samples, with a total of 602 participants with untreated hearing impairment, 672 participants with treated hearing impairment, 176 healthy controls, and 4,260 individuals with a range of hearing impairment with/without treatment. The results demonstrated that cognition is significantly poorer in (i) individuals with untreated hearing and remains poorer in (ii) treated hearing impairment compared to normal hearers. The degree of cognitive deficit is significantly associated with the degree of hearing impairment in both (iii) untreated and (iv) treated hearing impairment. Furthermore, (v) hearing intervention significantly improves cognition. Finally, (vii) hearing impairment impacted on all domains of cognition.

Conclusions: This meta-analysis suggests that hearing impairment is associated with cognitive problems. However, due to diversity within studies, small sample sizes, the failure to control for premorbid and other health factors, this conclusion may be premature.

Key words:

Cognition

Hearing

Association

Treatment

effects Meta -

analysis

INTRODUCTION

Hearing loss is common and often disabling, affecting over 1.23 billion people globally [1]. Increasing age is associated with increasing prevalence of significant hearing loss [2-5]. It is also associated with reduced quality of life [6, 7] and lowered mood [8]. In addition, epidemiological evidence suggests a relationship between peripheral hearing loss and cognitive function in adults over the age of 60. Such studies reveal poorer cognitive function in those with poorer hearing, using both verbal and non-verbally mediated tests, especially in memory and executive function [9-13], a faster rate of decline in cognition in adults aged from 55 years [14], and increased risk of incident, all-cause dementia [15, 16].

As might have been predicted, these findings have provided a catalyst for increased awareness of the potential mitigating role of hearing aids and cochlear implants as a protective strategy against cognitive decline. However, not all studies have found a significant relationship between hearing impairment and cognition, or a significant effect of intervention for hearing impairment on cognition, and a number of negative studies may go unpublished. Accordingly, meta-analysis of the published effects, also drawing on grey literature, is required. Moreover, there is considerable heterogeneity in the tasks and domains used to report cognitive function. Our meta-analysis sought to address this issue by, wherever possible, categorizing tasks within theoretically-driven cognitive domains.

The purpose of the current study was to examine the evidence-base regarding the relationship between hearing impairment and cognition and to consider the impact of hearing intervention on cognitive function, in order to clarify outcomes, and suggest directions for further research. To our knowledge, this is the first meta-analysis to explore the impact of hearing loss, and its treatment, on cognitive function.

Based on the types of studies published in the field, we asked, is cognition poorer in individuals with normal hearing compared to (i) individuals with untreated hearing impairment or (ii) with treated hearing impairment, is cognition associated with the degree of hearing impairment in (iii) untreated individuals and (iv) treated individuals, (v) is cognition poorer in people with untreated hearing impairment compared to individuals with treated hearing impairment, and (vi) does cognition improve after hearing intervention? Collapsing across the six study methodologies used above, we then divided cognition by domain, and asked (vii) is hearing impairment associated differentially with cognitive ability across different domains of cognition?

METHOD

Search Strategy

A systematic search of evidence from the research literature was performed per the Cochrane Collaboration guidelines and the PRISMA statement [17, 18]. Details of the search methodology are outlined in Figure 1.

An extensive, computer-assisted literature search was conducted using electronic databases (Keyword and MeSH explode) for published articles from January 1980 to April 2015 (Pubmed, CINAHL, EMBASE (Ovid), PsycINFO, Scopus, Academic Search Premier, The Cochrane Library, The Centre for Reviews and Dissemination). The electronic search was supplemented by hand-searching (references of included articles, contact with authors of unpublished studies). The grey literature was searched via OpenGrey and WHO ICTR databases. Unpublished studies were included in the search, to avoid publication bias.

A prospective protocol, outlining the proposed methodology and search strategy was completed and registered with the PROSPERO database [19]. This original protocol focused only on intervention studies. The search reported here was extended to include comparative and association studies. Some terms were piloted (‘cognition’, ‘dementia’, ‘hearing loss’, ‘hearing aid’, ‘aphasia’, ‘naming’, and ‘fluency’) but were not included in the final search as they did not capture an increased number of relevant articles than the final search terms. The final search terms ‘Memory OR Attention OR Executive Function OR Expressive Language OR Psychomotor Speed’ were combined with ‘Hearing OR Cochlear Implant’ and were found to capture a wide range of studies examining cognitive functions in individuals with hearing impairment. These papers included tests that had been mislabeled or used to measure other cognitive domains. The final search was limited to ‘English articles’ and ‘human research’.

Additionally, relevant articles were retrieved from the reference lists of studies included in the original search, conference proceedings and dissertations. Furthermore, key

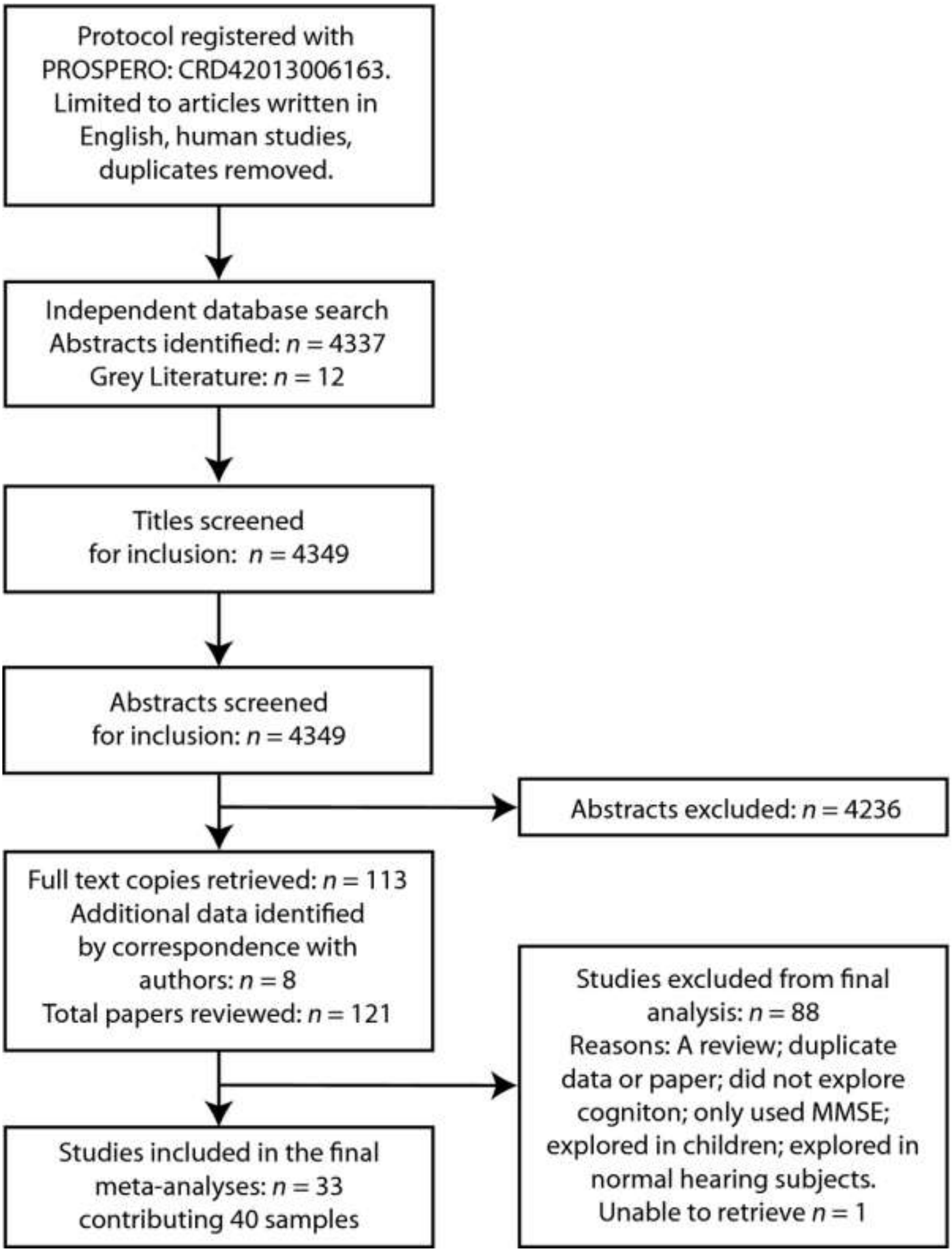

Figure 1.

Flow chart of article selection process.

authors who have published articles on the relationship between hearing and cognition were contacted; asking if they were aware of any other relevant published or unpublished studies.

Study selection criteria

The review included studies that assessed cognition in adults with treated and untreated hearing loss, studies that examined people with hearing loss before and after intervention, and studies that compared people with treated and untreated hearing loss to normal hearing individuals. Hearing loss is variously defined. Most recent epidemiology studies define a significant hearing loss as a mean hearing threshold of over 25dB for the four primary test frequencies involved in speech recognition (500, 1000, 2000 and 4000Hz) in the better ear [2-4]. This indicates a bilateral hearing loss. Clinically, hearing thresholds are loosely categorised into levels of severity [20], with a moderate or worse (>40dB averaged across the four primary thresholds) hearing loss often managed by hearing aids or hearing implants for those with severe to profound hearing loss.

Papers were excluded if the neuropsychological tests used were inadequately described such that acceptable validity and/or reliability could not be confirmed, if the paper was a review, or if it reported duplicate data (in this instance the most complete data set was selected). Studies were not considered if the data were presented in such a way that effect sizes could not be calculated, even after contact with the author. We contacted nine authors for further detail on eight research papers. Seven authors or their representatives replied. Of these, two had no more detail to provide, and five emailed further data.

Study Categorization

Titles generated by the search were scrutinized independently by three researchers (MO, RSB & CGBJ). Relevant abstracts were retrieved and assessed for suitability based on the inclusion and exclusion criteria. Discrepancies between reviewers were resolved through discussion: for 19 of the 121 given full paper reviews. This process led to the inclusion of 33 studies, and produced 40 samples (See Table 2).

These studies were categorized by sample type:

(i) Is cognition poorer in individuals with untreated hearing impairment compared to individuals with normal hearing? (n = 9) Examined in studies comparing two groups, a) people with untreated hearing impairment, and b) people with normal hearing.

(ii) Is cognition poorer in individuals with treated hearing impairment compared to those with normal hearing? (n = 5) Examined in studies comparing two groups, a) people with treated hearing impairment, and b) people with normal hearing.

(iii) Is cognition associated with degree of hearing impairment in untreated individuals? This question used studies examining associations between cognition scores and severity of hearing impairment (n = 5).

(iv) Is cognition associated with degree of hearing impairment in treated individuals? Studies examining associations between cognition scores and severity of hearing impairment in treated individuals were used (n = 14). Is cognition poorer in individuals with untreated hearing impairment compared to individuals with treated hearing impairment? (n = 3) Examined in studies comparing two groups, a) people with untreated hearing impairment, and b) people with treated hearing impairment.

(v) Does cognition improve after hearing intervention? (n = 4) Examined in studies testing cognition pre and post hearing intervention. None of which contained control samples.

In studies using association data, effect sizes are reported as *Pearson's r* values. For studies using group comparisons, effect sizes are reported as *Cohen's d* values. Due to few studies within each question and large test and cognitive domain heterogeneity, responses to these six questions could not be examined within individual cognitive domains. Instead, for each of questions (i) to (vi), cognition was examined as a unitary domain 'General Cognition', collapsing across all cognitive tests.

In order to examine differential harm across different cognitive domains, the studies were also divided by cognitive domain, but collapsing across all six types of study. Cognitive domains examined were 'Attention and Processing speed', 'Short Term and Working Memory', 'Long Term Memory', 'Executive Function', and 'Semantic Language and Knowledge' (each defined below). This subset of analyses explored one further question:

Table 1

The domains of cognition and tests that measure these domains used in the studies meta-analysed.

Category	Description	Tests that tap this cognitive skill
Attention and processing speed	Tasks that direct and maintain cognitive focus.	Test of everyday attention Trails A Sequence learning task TEACH Physical matching Symbol cancellation
Semantic processing and word knowledge	Tasks that tap into letter or word knowledge.	Semantic decision making Sentence completion task Word-word rhyme judgement Picture-word rhyme judgement Lexical decision making The test of silent word reading Passage comprehension test Phoneme detection test Name matching
Short term and working memory	Tasks that require the participant to hold information in short term stores and manipulate this information.	Reading span test Letter span test Digit span test The working memory test Free word recall (STM) Free and Cued Selective Reminding Test
Long term memory	Tasks that tap the ability to acquire and consolidate new information, or learning.	VVLT delayed AVLT 20 minute delay Action sentence recall Word recall after a delay Verbal sentence task
Executive functioning	These tasks measure one's ability to manage other cognitive processes, including memory and attention. Executive functions are responsible for volition, planning, purposeful action and monitoring effective performance.	Keep track task Letter-number sequencing SART inhibition task Digit span tasks Trails B Category and semantic fluency tasks Digit symbol substitution tasks CST interference task SCWT interference task Towers Stroop

(vi) How is hearing impairment associated with cognitive ability across different domains of cognition?

As this analysis grouped correlational and group difference data, effect sizes are reported as *Hedge's g.*

Categorisation of cognition

The domains of cognition assessed and the tests ascribed to these domains are presented in Table 1.

Attention and Processing Speed

Attention is an umbrella term referring to several capacities that enable an individual to become aware of, receptive to and concentrate on a particular stimulus, while ignoring other aspects of the environment [21, 22]. Processing Speed taps the ability speedily and accurately to perform simple tasks. It is essential for tasks requiring focused attention and concentration. Tasks assessing attention and processing speed typically gauge reaction times and responsiveness to stimuli [22].

Short Term Memory and Working Memory

Short-term memory refers to the ability to recall a small amount of information within about 30 s [21, 22]. This system is functionally and neurologically separate from the ability to store and recall information for more than 30 s, which is supported by encoding into long-term memory stores [21, 22].

Working memory involves actively holding information in short-term memory stores, while dynamically manipulating this information. One such task of working memory is 'digit span backwards', which requires an individual to repeat a sequence of numbers in reverse order [21, 22].

Long Term Memory

Long-term memory refers to the acquisition and consolidation of new information, or learning [22].

Executive Function

Executive functions collectively manage other cognitive processes, including memory and attention, and are responsible for volition, planning, purposeful action and monitoring effective performance [21, 22].

Semantic and Language Knowledge

Semantic and language knowledge refers to the capacity to acquire, comprehend and produce complex symbolic systems for communication [21, 22]. Tests measure the capacity to produce and understand language under structured conditions, such as naming or verbal fluency [21, 22].

Data Extraction and Processing

Data Extraction

Data extracted and coded from the final articles included author/s, whether published or not, journal and year of publication (if applicable), study design, sample size, participant details when available, and neuropsychological assessments employed. See Table 2 for sample details. Correlations or beta weights, means, standard deviations and sample size were extracted to examine the relationships between the variables of interest.

Data Processing

Comprehensive Meta-Analysis version 2.2.064 [23] was used to synthesize data, calculate effect sizes, create forest plots and funnel plots, examine publication bias and the effect of moderators on effect sizes.

Table 2
Papers and samples included in the meta-analysis with descriptive details.

Author and sample details	Question	N	N Male	M age (yrs)	Data	Cognitive domain	Hearing test
Lunner, 2003; *hearing impairment after intervention*	iv	72	40	67	r	Semantic and language knowledge, Working memory	SNR in noise
Lunner, 2003; *hearing impairment before intervention*	iv	42	xx	66	r		
Koo et al., 2008; *hearing*	i	17	4	26.5	M, SD	Working memory, Semantic and language knowledge	Audiogram
Koo et al., 2008; *deaf (no intervention)*	i	30	17	25.8			
Andersson and Lyxell, 1998; *hearing impaired (assume not treated)*	i	18	1	53	M, SD	Semantic and language knowledge, Short term memory, Working memory	Audiogram
Andersson and Lyxell, 1998; *normal hearing*	i	18	1	53			
Andersson and Lyxell, 1999; *hearing impaired (assume not treated)*	i	16	1	52	M, SD	Semantic and language knowledge	Audiogram
Andersson and Lyxell, 1999; *normal hearing*	i	16	1	52			
Cervera et al., 2009; *range of hearing ability*	iv	55	xx	40.8	r	Short term memory, Working memory	PTA4
Valentijn et al., 2005; *range of hearing ability*	iv	391	199	65.1	r	Executive functioning, Semantic and language knowledge, Attention/ Processing Speed	PTA thresholds
Gatehouse et al., 2006; *post hearing intervention*	iv	50	xx	xx	r	Short term memory	Hearing loss factor
Larsby et al., 2005; *young normal hearing*	i	12	xx	29.5	M, SD	Semantic and language knowledge	xx
Larsby et al., 2005; *young hearing loss no intervention*	i	12	xx	30.3			
Larsby et al., 2005; *elderly normal hearing*	i	12	xx	69.0			
Larsby et al., 2005; *elderly hearing loss, no intervention*	i	12	xx	70.3			
Van Boxtel et al., 2000; *range of hearing ability*	iv	453	223	51.4	r	Attention/ Processing Speed, Short term memory	Pure tone conduction thresholds
Knutson et al., 1991; *hearing impaired with Cochlear implant*	iv	29	xx	52.1	r	Semantic and language knowledge, Attention/ Processing Speed, IQ	Sentence, consonant, vowel and phoneme audiological test
Lyxell et al., 1994; n*ormal hearing*	i	22	9	xx	M, SD	Semantic and language knowledge	Medical records
Lyxell et al., 1994; *hearing impaired no intervention*	i	15	8	xx			
McCoy et al., 2013; b*etter hearing*	i	12	4	72.9	F, sig.	Semantic and language knowledge	PTA
McCoy et al., 2013; *hearing loss no intervention*	i	12	4	72.9			
Neher et al., 2009; *hearing impaired with cochlear implant*	iii	20	xx	60	r	Working memory, Attention/ Processing Speed	SRT Dantale II
Ronnberg et al., 2011; *hearing aid wearers*	ii	160	xx	xx	M, SD	Memory, Executive functioning, Semantic and language knowledge	xx
Ronnberg et al., 2011; *population sample*	ii	2,756	xx	xx			

Rudner et al., 2009; *hearing impaired after intervention*	iii	32	12	70	r	Working memory, Attention/ Processing Speed	PTA7
Rudner et al., 2008; *hearing impaired after intervention*	iii	102	xx	65	r	Working memory, Attention/ Processing Speed	PTA
Van Hooren et al., 2005; *hearing impaired after intervention*	iv	56	36	72.5	F, sig.	Attention/ Processing Speed, Executive functioning, Semantic and language knowledge	xx
Van Hooren et al., 2005; *hearing impaired without intervention*	iv	46	29	74.5			
Lyxell et al., 1996; *hearing impaired without intervention*	i	10	xx	xx	M, SD	Semantic memory, Short term memory, Working memory	xx
Lyxell et al., 1996; *normal hearing*	i	10	xx	xx			
Kramar et al., 2009; *hearing impaired without intervention*	iv	44	10	25	r	Short term memory, Working memory	xx
Gatehouse et al., 2003; *hearing impaired without intervention*	iv	50	xx	xx	r	Short term memory, Working memory	xx
Humes and Coughlin, 2009; *hearing impaired without intervention*	iv	19	xx	75.1	r	Attention/ Processing Speed, Short term memory, Working memory	xx
Ng et al., 2013 thesis paper 3; *hearing impaired without intervention*	iv	26	11	59	r	Short term memory, Working memory	PTA
Ng et al., 2013 thesis paper 4; *hearing impaired without intervention*	iv	27	xx	xx	r	Short term memory, Working memory, Semantic memory	PTA
Ng et al., 2014; *hearing impaired before and after intervention*	iv	27	20	67.2	r	Attention/ Processing Speed, Semantic Memory, Short term memory, Working memory	PTA
Foo et al., 2007; *hearing impaired without intervention*	iv	32	12	70.3	r	Short term memory, Working memory	xx
Dawes et al., 2014; *hearing impaired after intervention*	iv	17	xx	73	r	General cognition	FAAF
Hua et al., 2014; *hearing impaired without intervention*	ii	20	10	44.3	t, sig.	Executive function, Semantic memory, Short term memory, Working memory	PTA
Hua et al., 2014; *normal hearing*	ii	20	11	44.3			
Ferguson et al., 2014; *hearing impaired after intervention and before/after intervention*	v,vi	23	29	50-74	M, SD	Attention/ Processing Speed, Short term memory, Working memory	PTA
Ferguson et al., 2014; *hearing impaired without intervention*	v,vi	21					
Lin, 2011; *range of hearing impaired with/without intervention*	iii	605	285	64.1	r	Executive function	NHANES protocol

Moradi et al., 2014; *hearing impaired with intervention*	ii	24	13	72.4	M, SD	Short term memory, Working memory	PTA
Moradi et al., 2014; *normal hearing*	ii	24	13	71.5			
Woods et al., 2013; *hearing impaired without intervention*	i	16	xx	60	N, sig.	Attention/ Processing Speed, Executive function, Short term memory, Working memory	xx
Woods et al., 2013; *normal hearing*	i	10	xx	36			
Tesch-Romer et al., 1997; *normal hearing*	i,ii,v,vi	28	43%	69.4	M, SD	Executive function	xx
Tesch-Romer et al., 1997; *hearing impaired without intervention and hearing impaired before/after intervention*	i,ii,v,vi	70		71.8			
Tesch-Romer et al., 1997; *hearing impaired with intervention*	i,ii,v,vi	42		71.5			
Benichov et al., 2012; *hearing impaired without intervention*	iii	53	24	56.1	r	General cognition	HF PTA
Young-Choi et al., 2011; *hearing impaired without intervention and before/after intervention*	v,vi	11	xx	63.1	M, SD	Long term memory	WIN test
Young-Choi et al., 2011; *Hearing impaired after intervention*	v,vi	18		69.5			

Note: 'xx' indicates data were not available; r = correlations reported; M = mean; SD = standard deviation; sig. = significance; F = ANOVA F test reported; PTA4/7 = pure tone average, using 4 or 7 frequencies, HF high frequency; FAAF = Four Alternative Auditory Features test; SRT = Sound Recognition in noise Threshold; Question = the question for which the paper provided data; All papers were used in question vii, see the column 'Cognitive domain' to see which domains were assessed.

Calculation of Effect Sizes

Random effect sizes were calculated [24]. In the present meta-analysis, samples differed on such variables as type of hearing intervention, length of time with hearing impairment, length of time with treatment, age, gender and screening measures. As such, a random effects model was chosen to account for these differences. Moderator analyses were used to explore the effect of these study differences on effect size estimates. Due to small sample sizes when dividing by study design (i.e., questions i-vi) moderator analyses were explored using all studies.

Where estimates of effect size are given as *Cohen's d* (Questions i, ii, v and vi) or *Hedges's g* (Question vii) [*Pearson's r* effect sizes (Questions iii and iv) are provided in parentheses], effect sizes of ≥ 0.20 ($r \geq 0.10$) are considered small, ≥ 0.50 ($r \geq 0.24$) medium, ≥ 0.80 ($r \geq 0.37$) large and ≥ 1.00 ($r \geq 0.45$) very large [25]: the closer to zero the scores, the smaller the difference between groups (or the associations found).

Heterogeneity

Heterogeneity of effect sizes measures the difference between the true effect size in the population and the statistically observed effect size [26]. Statistical estimates of heterogeneity were obtained using Cochrane's Q statistic, the T^2 and I^2 statistics. When the Q statistic is significant, this suggests there is a significant difference between the observed and true effect. However, the Q statistic is vulnerable to small sample size, hence T^2, which measures the magnitude of heterogeneity, and I^2, which estimates the proportion of real variance caused by extraneous study variables such as age or test used, can be calculated [26]. If Q was significant, T^2 and I^2 were examined to quantify the degree of heterogeneity.

Risk of Publication Bias

Research suggests that studies with large samples, and/or significant results are more likely to be published, and thus available for meta-analysis [26]. Publication bias was inspected visually using funnel plots, and statistically through Egger's test for asymmetry [27].

RESULTS

Description of Studies

The 33 studies contributed 40 samples (see Figure 1), and a total of 5,735 participants with a of mean Age 57.7 (±27.0) years. These samples contributed 602 participants with untreated hearing impairment, 672 participants with treated hearing impairment, 176 healthy controls, and 4,260 individuals with a range of hearing impairment. Details on individual studies are provided in Table 2.

Meta Analyses

Individuals with normal hearing had better general cognition than individuals with both (i) untreated (d = .54, medium effect) and (ii) treated hearing impairment (d = .20, small effect). Better hearing in (iii) untreated individuals was associated with better cognition (r = .21, small effect), as was better hearing in (iv) treated individuals (r = .25, medium effect). Further, (v) individuals with treated hearing impairment had better hearing than individuals with untreated hearing impairment (d = .22, small effect). For Questions (i) to (v), heterogeneity and publication bias were non-significant (see Table 3).

Hearing intervention (vi) significantly improved cognition (d = .49, small effect). Heterogeneity was non-significant, however, there was evidence of publication bias (see Table 3). As publication bias was an issue, Duval and Tweedie's trim and fill and the Classic fail safe N were examined. The Duval and Tweedie estimate suggested a reduction in effect size when publication bias was corrected, d = 0.23 (CI lower -0.19, upper 0.66), however, this effect size remained significant. The Classic fail safe N suggested that just 8 non-significant studies would be required to bring the effect size to non-significance.

Finally, irrespective of study design, (vii) better hearing was associated with better performance in Attention/Processing Speed (g = .47), Short Term/Working Memory (g = .45), Long Term Memory (g = .40), Executive Function (g = .24), Semantic Processing and Word Knowledge (g = .32) (See Table 4). Effects were small for all domains.

Table 3

Mean effect sizes, heterogeneity and publication bias statistics for questions (i) to (vi).

Domain (*effect*)		Effect Size Statistics					Heterogeneity Statistics				Publication Bias			
	N	d/r	95% CI		Z	*p*	Q (df)	*p*	T^2	I^2	Intercept	95% CI		*p*
			L	U								L	U	
Question i (d)	9	0.54	0.31	0.77	4.97	<0.001	5.83 (8)	0.67	0	0	0.71	-1.65	3.08	0.50
Question ii (d)	5	0.20	0.07	0.33	3.05	0.002	0.83 (4)	0.94	0	0	-0.44	-1.59	0.71	0.31
Question iii (r)	5	0.21	0.07	0.35	2.87	0.004	8.30 (4)	0.81	0.01	51.78	0.96	-2.66	4.57	0.46
Question iv (r)	14	0.25	0.16	0.33	5.60	<0.001	21.30 (13)	0.07	0.01	38.93	-1.00	-2.19	0.19	0.09
Question v (d)	3	0.22	-0.08	0.52	1.45	0.148	0.68 (2)	0.71	0	0	-0.30	-21.82	21.22	0.89
Question vi (d)	4	0.49	0.07	0.92	2.26	0.024	6.14 (3)	0.12	0.09	51.12	3.17	1.12	5.22	0.02

Note. Effect sizes of $d \geq 0.20$ (or $r \geq 0.10$) are considered small, $d \geq 0.50$ (or $r \geq 0.24$) medium, $d \geq 0.80$ ($r \geq 0.37$) large and $d \geq 1.00$ ($r \geq 0.45$) very large. CI = Confidence Interval; L = Lower CI; U = Upper CI.

Table 4

Mean effect sizes, homogeneity and publication bias statistics for each cognitive domain (Question vii).

Domain (*effect*)		Effect Size Statistics					Heterogeneity Statistics				Publication Bias			
	N	g	95% CI		Z	*p*	Q (df)	*p*	T^2	I^2	Intercept	95% CI		*p*
			L	U								L	U	
A/P (g)	10	0.64	0.41	0.87	5.43	<0.001	19.43 (9)	0.02	0.06	53.67	-0.81	-3.36	1.15	0.37
STM/WM (g)	29	0.45	0.29	0.61	5.58	<0.001	7.13 (28)	<0.01	0.09	61.18	0.51	-0.57	1.59	0.34
LTM (g)	6	0.40	0.12	0.69	2.81	0.005	18.19 (5)	0.01	0.07	72.51	-0.92	-5.15	3.30	0.58
EF (g)	12	0.24	0.16	0.32	5.62	<0.001	11.49 (11)	0.40	0.01	4.29	-0.86	-2.43	0.52	0.18
Semantic (g)	13	0.32	0.19	0.44	5.07	<0.001	10.61 (12)	<0.01	0	0	0.90	0.17	1.63	0.02

Note. Semantic = Semantic Processing and Word Knowledge; STM/WM = Short Term Memory or Working Memory; A/P = Attention/Processing Speed; LTM = Long Term Memory. Effect sizes of $g \geq 0.20$ are considered small, $g \geq 0.50$ medium, $g \geq 0.80$ large and $g \geq 1.00$ very large. CI = Confidence Interval; L = Lower CI; U = Upper CI; x = insufficient data to run these analyses.

With the exception of Semantic Processing and Word Knowledge, publication bias was not noted. The Duval and Tweedie estimate suggested a reduction in the Semantic Processing and Word Knowledge effect size following correction for publication bias, d = 0.27 (CI lower 0.09, upper 0.43), however, this effect size remained significant. The Classic fail safe N suggested that 80, non-significant studies would be required to bring the effect of hearing impairment on Semantic Processing and Word Knowledge to non-significance.

Except for Executive Function, all domains demonstrated significant heterogeneity. As such, potential moderators of the effect size were examined.

Moderator analyses

Categorical moderators examined were: type of treatment (Cochlear Implant (1) or hearing aid (2)); length of time with treatment (0-3 months (1), 4 - 6 months (2), 7 - 12 months (3), ≥ 13 months (4)); task type (visual (1) or verbal (2)); and, age (younger ≤49 (1) or older ≥50 years (2)). These moderators were chosen as they differed across many studies and might impact upon performance.

Age was not a moderator of the relationship between hearing and cognition (Q(3) = 2.49, p = 0.47), nor was 'time with treatment' (Q(4) = 2.16, p= 0.71), or 'task type' (Q(3) = 3.81, p = 0.28). There was insufficient detail about the 'type of treatment' used, many studies with mixed treatments, and insufficient hearing aid studies, to explore treatment type as a moderator effectively.

DISCUSSION

This is the first meta-analysis to explore the impact of hearing loss and hearing intervention on cognition. We included both published and grey literature.

Summary of main results

Overall, results indicate that individuals with hearing loss have poorer cognition compared to individuals with normal hearing, whether or not that hearing loss is treated. However, the size of the difference compared to normal hearers was less than half in treated hearing impaired samples than in untreated. Correlational data reveal a dose-response relationship between the degree of hearing impairment (whether in those being treated or not) and general cognition. As might be expected, poorer hearing was significantly associated with poorer general cognition, albeit the effects were not large, on average explaining just 4.4 (untreated) to 6.3 (treated) percent of variance. At the group level, individuals with treated hearing impairment demonstrate superior cognition to those with untreated hearing impairment: this effect being of similar magnitude to the difference between treated and normal hearers, suggesting that treatment improves cognitive outcomes but does not remediate all problems. Consistent with this positive view of treatment, cognition improves in individuals assessed pre and post intervention. On the face of it, this effect is one of the strongest reported (0.49) but was based on just 4 studies, with evidence of publication bias. Analysis revealed that 8 negative studies would be sufficient to make this apparent improvement zero, and an adjustment for publication bias suggested the effect in these four studies may be closer to half of the size found (0.23).

When we considered the impact of hearing impairment on a cognitive domain by domain basis, results revealed that better hearing is associated with better performance across all cognitive domains examined, including attention and processing speed, short term/working, and long term memory, executive functioning and, semantic processing and word knowledge, although the effects were all small. These effects were not impacted by the age of the participants, the time with treatment, or whether the tasks were 'visual' or 'verbal' in nature.

Overall completeness and applicability of evidence

Whilst meta-analysis is a robust means of determining the weighted average effect of hearing impairment or its treatment on cognition, the number of studies in some of these meta-analyses was small. For example, the conclusion that there was a difference in cognition between those with treated and those with untreated hearing impairment was based on just 3 studies. However, the weight of evidence across all meta-analyses offers two consistent findings: that hearing impairment is associated with cognitive difficulties and that treatment improves cognitive outcome. What the evidence cannot reveal is the mechanisms by which hearing impairment and cognition are related.

Quality of evidence

Measurement of cognition

Large differences were observed in the selection of cognitive test measures (see Table 1). The choice of outcome measure is crucial, since selecting tests incorrectly may lead to incorrect measurement of cognition, and/or insensitive measures and, accordingly, erroneous findings. Perhaps, driving this lack of consistency in test selection is an absence of a theory-based argument for which cognitive domains are affected in hearing impairment and require investigation. Of note, very few of the studies outlined a clear rationale for why they assessed the particular aspect of cognition reported or, indeed, why they used a particular method of assessing hearing impairment (with the exception of Lin et al. [10, 11, 14]). Until a sufficient number of studies, using the same well-justified cognitive measures, is available, there will continue to be a lack of clarity in this field.

Further to this point, many of the studies used cognitive tasks produced and normed for a hearing population. Many of these tasks involve hearing a stimulus and responding in an accurate and timely fashion. When used with hearing impaired individuals, the validity of any results must be questioned. It is possible that we are arguing in a circular fashion that tasks that involve hearing are harder for people who are hearing impaired. Further, hearing impairment (even when treated) may require greater cognitive resources to complete the tasks well. Thus, the reported differences could be due to the degree to which coping with a hearing impairment uses up processing capacity rather than due to an underlying cognitive difficulty: that is, the cognitive effects may be secondary rather than primary consequences of hearing impairment. The present results support this, as the biggest differences between groups existed in the Attention/Processing Speed domain, although this effect was still small. These domains would suffer most when tasks are cognitively demanding or when processing resources are being directed towards managing hearing impairment. To this end, tasks that have been developed with a visual alternative may be a better test of cognition, and may have greater ecological validity for this population. When more data are available in this field, it will be possible to meta-analyse findings dividing results into greater hearing and less-hearing dependent cognitive assessments. As reported above, however, there was no impact on the effects found when visual tasks were contrasted with verbal: a point we reflect on below.

Moderation analyses

Moderation analysis allows for exploration of differences between studies. Whilst a limited set of moderators was considered for this meta-analysis, important areas for future exploration could include examination of the possible influence of variables including pre- and post-lingual hearing impairment, verbal and non-verbal IQ, oral and manual communication, mood, cognitive reserve, education, and the number of health conditions. Many of these variables have demonstrated effects upon cognitive performance in examinations of the relationship between hearing and cognition in children [28] and upon cognition more broadly [8].

The moderator analyses indicate that the type of task (visual or verbal), the length of time with treatment, and participant age did not impact on the relationship between cognitive performance and hearing. However, this does not mean that effects would not be different had such factors been examined *within* studies, since moderation analysis can only compare *between* studies. Studies manipulating cognitive load, length of time with treatment and with tight control of inter-individual variables such as age and cognitive reserve will provide more insight into these questions.

Potential biases in review

The searches were carefully conducted to include both published and grey literature and selection was checked between the authors, reducing the risk of bias in the findings. However, the most powerful assessment of whether intervention improves cognition in hearing impairment is a blinded, randomised controlled trial. None of the studies reported were of this kind. Thus, improvements may have related to practice effects, or other bias. Such prospective, randomised, controlled studies should use sensitive cognitive measures, selected based on a theoretical account of the mechanisms by which hearing impairment impacts on cognition.

The present meta-analysis did not separate reaction time data from accuracy data. Division of reaction time and accuracy would permit greater understanding of the cognitive profile of individuals with hearing impairment. As noted above, one proposed mechanism by which hearing loss may impact on cognition is that attentional or short-term/working memory resources are required to compensate for auditory processing deficits [12, 13, 29, 30]. This may manifest either as slowed response times or impaired accuracy. Accordingly, it will be important, in future studies, to separate out response time and accuracy data. This will require focusing on one or two key study designs (ideally pre-post randomized, controlled intervention studies, of which there are currently none), and well-chosen cognitive outcomes.

Implications for research and clinical practice

The present research was inspired by evidence (e.g. [10, 11, 14]) that hearing impairment impacts cognition. Such a claim has substantial implications for best treatment recommendations, quality of life, social involvement, and lifetime cognitive health. Whilst the results from the present paper are preliminary, they do lend support to the interplay of cognition and hearing. Critically, if hearing impairment is a primary cause of cognitive dysfunction, this is likely to have a reciprocal impact on the management of hearing impairment. What such findings cannot do, however, is speak to the proposed mechanisms by which impaired hearing is related to impaired cognition. Studies that investigate the proposed mechanisms (e.g. social isolation [10, 14]) are urgently required.

Previous research shows that cognition influences cochlear implant outcomes, with higher verbal learning and working memory performance associated with better speech outcomes at six months post implantation [31], that it influences the communication benefit gained from hearing aids [32], and that working memory and phonological processing speed are important predictors of speech understanding for older adults [33]. Furthermore, there are reports showing that simplifying the programming of key hearing aid features for individuals with reduced cognitive ability is beneficial [34-38].

A recent, retrospective, multi-centre study sought to determine the most important factors predicting hearing rehabilitation outcomes [39]. Hearing-related factors explained 22% of the variance in outcomes, and the authors speculated that some of the remaining 78% might be the result of variability in test measures and methods, and "*higher order cognitive reorganization*" (*pp.* 10): both unaccounted for in large scale, clinical data collection to date. These findings underscore the need to understand the role of cognition in hearing outcomes, as it may be a key predictor of success in ways we have been unable to measure consistently. That is, hearing impairment may both reduce cognitive capital *and* reduce the resources available to individuals to deal with that hearing impairment.

Conclusions

The present meta-analysis suggests that hearing impairment is implicated in cognitive problems. While Lin and colleagues [10, 11, 14] have argued that this could be a causal relationship, this conclusion may be premature. Due to the diversity within studies (samples, measurement of cognition, hearing intervention etc.), the failure to control for premorbid and other health factors, further research is required to understand whether hearing impairment is a *cause* of cognitive deficits, how it confers this risk, and whether hearing intervention mitigates any effects on cognitive function.

References

Vos T., Barber R.M., Bell B. *et al.* (2015) Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet*. **early online**

Gopinath B., Rochtchina E., Wang J.J., Schneider J., Leeder S.R. & Mitchell P. (2009) Prevalence of age-related hearing loss in older adults: Blue Mountains Study. *Arch. Intern. Med.* **169,** 415-416

Agrawal Y., Platz E.A. & Niparko J.K. (2008) Prevalence of hearing loss and differences by demographic characteristics among US adults: data from the National Health and Nutrition Examination Survey, 1999-2004. *Arch. Intern. Med.* **168,** 1522-1530

Wilson D.H., Walsh P.G., Sanchez L. *et al.* (1999) The epidemiology of hearing impairment in an Australian adult population. *Int. J. Epidemiol.* **28,** 247-252

Cruickshanks K.J., Nondahl D.M., Tweed T.S. *et al.* (2010) Education, occupation, noise exposure history and the 10-yr cumulative incidence of hearing impairment in older adults. *Hear. Res.* **264,** 3-9

Gopinath B., Schneider J., McMahon C.M., Teber E., Leeder S.R. & Mitchell P. (2012) Severity of age-related hearing loss is associated with impaired activities of daily living. *Age Ageing*. **41,** 195-200

Hua H., Karlsson J., Widen S., Moller C. & Lyxell B. (2013) Quality of life, effort and disturbance perceived in noise: a comparison between employees with aided hearing impairment and normal hearing. *Int. J. Audiol.* **52,** 642-649

Preminger J.E. & Meeks S. (2010) The influence of mood on the perception of hearing-loss related quality of life in people with hearing loss and their significant others. *Int. J. Audiol.* **49,** 263-271

Gussekloo J., de Craen A.J., Oduber C., van Boxtel M.P. & Westendorp R.G. (2005) Sensory impairment and cognitive functioning in oldest-old subjects: the Leiden 85+ Study. *Am. J. Geriatr. Psychiatry*. **13,** 781-786

Lin F.R. (2011) Hearing loss and cognition among older adults in the United States. *J. Gerontol. A Biol. Sci. Med. Sci.* **66,** 1131-1136

Lin F.R., Ferrucci L., Metter E.J., An Y., Zonderman A.B. & Resnick S.M. (2011) Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology*. **25,** 763-770

Lindenberger U. & Baltes P.B. (1994) Sensory functioning and intelligence in old age: a strong connection. *Psychol. Aging*. **9,** 339-355

Tay T., Wang J.J., Kifley A., Lindley R., Newall P. & Mitchell P. (2006) Sensory and cognitive association in older persons: findings from an older Australian population. *Gerontology*. **52,** 386-394

Lin F.R., Yaffe K., Xia J. *et al.* (2013) Hearing loss and cognitive decline in older adults. *JAMA Intern Med*. **173,** 293-299

Lin F.R., Metter E.J., O'Brien R.J., Resnick S.M., Zonderman A.B. & Ferrucci L. (2011) Hearing loss and incident dementia. *Arch. Neurol.* **68,** 214-220

Gallacher J., Ilubaera V., Ben-Shlomo Y. *et al.* (2012) Auditory threshold, phonologic demand, and incident dementia. *Neurology*. **79,** 1583-1590

Higgins J.P.T., Green S. & Cochrane Collaboration. (2008) *Cochrane handbook for systematic reviews of interventions*. John Wiley & Sons Ltd.: Cochrane Collaboration, Chichester, Oxford

Moher D., Liberati A., Tetzlaff J., Altman D.G. & Group P. (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann. Intern. Med.* **151,** 264-269, W264

Taljaard D., Brennan-Jones C.G., Bucks R., Eikelboom R.H. & Atlas M.D. (2013) Does hearing intervention improve cognitive function? A systematic review protocol. *PROSPERO* CRD42013006163

Clark J.G. (1981) Uses and abuses of hearing loss classification. *ASHA*. **23,** 493-500

Lezak M.D. (1995) *Neuropsychological assessment*. 3rd edn. Oxford University Press, New York

Strauss E., Sherman E.M.S., Spreen O. & Spreen O. (2006) *A compendium of neuropsychological tests : administration, norms, and commentary*. 3rd edn. Oxford University Press, Oxford ; New York

Borenstein M., Hedges L.V., Higgins J.P.T. & Rothstein H.R. (2005) Comprehensive Meta-Analysis Version 2. Biostat, Engelwood, NJ

Rosenthal R. (1995) Writing Metaanalytic Reviews. *Psychol. Bull.* **118,** 183-192

Cohen J. (1977) *Statistical power analysis for the behavioral sciences*. Rev. edn. Academic Press, New York

Borenstein M. (2009) *Introduction to meta-analysis*. John Wiley & Sons, Chichester, U.K.

Egger M., Smith G.D., Schneider M. & Minder C. (1997) Bias in meta-analysis detected by a simple, graphical test. *Br. Med. J.* **315,** 629-634

Khan S., Edwards L. & Langdon D. (2005) The cognition and behaviour of children with cochlear implants, children with hearing aids and their hearing peers: a comparison. *Audiol. Neurootol.* **10,** 117-126

Tun P.A., McCoy S. & Wingfield A. (2009) Aging, hearing acuity, and the attentional costs of effortful listening. *Psychol. Aging*. **24,** 761-766

Wingfield A., Tun P.A. & McCoy S.L. (2005) Hearing Loss in Older Adulthood - What It Is and How It Interacts With Cognitive Performance. *Curr. Dir. Psychol. Sci.* **14,** 144-148

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. *Audiol. Neurootol.* **12,** 254-264

Akeroyd M.A. (2008) Are individual differences in speech reception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing-impaired adults. *Int. J. Audiol.* **47 Suppl 2,** S53-71

Humes L.E. (1991) Understanding the speech-understanding problems of the hearing impaired. *J. Am. Acad. Audiol.* **2,** 59-69

Foo C., Rudner M., Ronnberg J. & Lunner T. (2007) Recognition of speech in noise with new hearing instrument compression release settings requires explicit cognitive storage and processing capacity. *J. Am. Acad. Audiol.* **18,** 618-631

Gatehouse S., Naylor G. & Elberling C. (2003) Benefits from hearing aids in relation to the interaction between the user and the environment. *Int. J. Audiol.* **42 Suppl 1,** S77-85

Moore B.C. (2008) The role of temporal fine structure processing in pitch perception, masking, and speech perception for normal-hearing and hearing-impaired people. *J Assoc Res Otolaryngol*. **9,** 399-406

Ng E.H., Rudner M., Lunner T. & Ronnberg J. (2013) Relationships between self-report and cognitive measures of hearing aid outcome. *Speech Lang Hear*. **16,** 197-207

Rudner M., Ronnberg J. & Lunner T. (2011) Working memory supports listening in noise for persons with hearing impairment. *J. Am. Acad. Audiol.* **22,** 156-167

Lazard D.S., Vincent C., Venail F. *et al.* (2012) Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: a new conceptual model over time. *PLoS One*. **7,** e48739