A novel study on association between untreated hearing loss and cognitive functions of older adults: Baseline non-verbal cognitive assessment results

D.M.P. Jayakody[1,2,*], P.L. Friedland[1,2,3], R.H. Eikelboom[1,2,4], R.N. Martins[5], H.R. Sohrabi[5]

[1]Ear Science Institute Australia, Subiaco, WA, Australia;
[2]Ear Sciences Centre, School of Surgery, The University of Western Australia, Crawley, WA, Australia;
[3]Department of Otolaryngology Head Neck Skull Base Surgery, Sir Charles Gairdner Hospital, Nedlands, WA, Australia;
[4]Department of Speech-Language Pathology and Audiology, University of Pretoria, Pretoria, South Africa;
[5]School of Medical and Health Sciences, Edith Cowan University, Joondalup, WA, Australia

*Correspondence:
D.M.P. Jayakody, Ear Science Institute Australia, Subiaco, WA, Australia. Email: dona.jayakody@earscience.org.au

Abstract

Background: Age-related hearing loss (ARHL) is highly prevalent in older adults and more than two-thirds above age 70 years suffer from ARHL. Recent studies have established a link between ARHL and cognitive impairment, however, most of the studies have used verbally loaded cognitive measures to investigate the association between ARHL and cognition. It is possible that due to hearing impairment, the elderly may experience difficulty in following verbal instructions or completing tasks that heavily rely on hearing during cognitive assessments. This may result in over-estimation of cognitive impairment in such individuals. This baseline cross-sectional study investigated the associations between untreated hearing loss and a number of cognitive functions using a battery of non-verbal cognitive tests. Further, association between hearing loss and psychological status of older adults was examined.

Study design: Prospective case-controlled study.

Methods: A total of 119 participants (54 males, M = 66.33 + 10.50 years; 65 females M = 61.51 + 11.46

years) were recruited. All participants completed a hearing assessment, a computerised test battery of non-

auditory cognitive functions and the depression, anxiety and stress scale.

Results: Hierarchical multiple regression analysis results revealed that hearing thresholds significantly associated with the working memory (P<.05), paired associative learning scores (P<.05), depression (P <.001), and anxiety (P<.001) and stress (P<.001) scores. Analysis of covariance results revealed that participants with moderately-severe hearing loss performed significantly poorer in paired associative learning and working memory tasks and psychological function tests compared to those with normal hearing.

Conclusion: Results of the current study suggest a significant relationship between ARHL and both cognition and psychological status. Our results also have some implications for using non-verbal cognitive tests to evaluate cognitive functions in postlingually hearing impaired ageing adults, at least for those with more than moderately-severe levels of hearing loss.

Keywords: Hearing loss, cognition, depression, anxiety, stress

Keypoints

ARHL is highly prevalent in older adults.

ARHL is associated with cognitive impairment.

ARHL is also associated with poor psychological functions.

Introduction

Recent evidence indicates that age-related decline in the olfactory, visual and auditory sensory modalities may precede cognitive impairment associated with Alzheimer's disease (AD) and such decline may even signal the increased risk of developing AD.[1] Hearing loss has been considered one of the most highly prevalent sensory impairments in older adults[2] with approximately 40% to 45% of adults aged 65 years and 83% of adults aged 70 years and above affected.[3] A number of cross sectional[4,5] and longitudinal[4-6] studies have reported an association between peripheral hearing and cognitive impairment, with a single exception being the two-year follow-up of the Australian Longitudinal Study of Ageing. [7] A recent meta-analysis conducted by Taljaard et al[8] on 33 studies reported an association between hearing loss and cognitive impairment. Further, the rate of decline in cognitive functions is associated with the rate of decline in hearing.[9] Prospective longitudinal studies have reported an association between the risk of incident dementia and hearing loss[6,10] and risk of incident AD (1.20 increase per 10 dB loss; 95% CI 0.94-1.53).[6]

Many attempts have been made to provide plausible explanations for the association between age-related hearing loss (ARHL) and cognitive impairment in dementia and AD. Lindenberger and Baltes[11] proposed three potential hypotheses to explain the strong relationship between ageing and decline in cognition including, i) sensory deprivation, ii) common cause and iii) age-induced cognitive load with the common-cause. It has been suggested that general age-related neuropathological changes in the brain may actually explain this relationship, but current data do not support this general domain and function specific underlying mechanism theory.[12] Recently, two more hypotheses have been proposed to explain the relationship between hearing loss and cognitive decline. Rönnberg and colleagues[13] introduced the "ɪnteractive hypothesis", emphasising an online interaction between hearing-related perceptual aspects and cognitive functions. The perceptual

degradation mechanism hypothesis asserts that in individuals suffering from hearing loss, even audibility of the stimulus does not improve memory and encoding processes.[14] However, given the complex relationship between ARHL and cognition, it is difficult to establish an underlying causal mechanism to explain this association.[15] In summary, the gradual decline in cognition and hearing abilities, as a function of ageing, reported to be mediated through number of factors including social isolation, depression and cognitive over-load.[13]

Impaired communication ability resulted from untreated hearing loss increases the risk of psychological and socio-situational negative outcomes compared to normal hearing.[16,17] Hearing impairment has been linked to depression[17,18] and social isolation.[19] By using structural equation modelling, Dawes et al[18] found that depression and social isolation were also associated with poor performance in cognitive functions. Altogether, these results indicate that psycho-social negative consequences of ARHL are also contributing to further cognitive impairment.

Hearing loss influences the participant's performance during cognitive assessments.[20,21] However, most commonly used cognitive assessments use both auditory or visual test stimuli.[21] For example, the Mini-Mental State Examination (MMSE) and Montreal Cognitive Assessment (MoCA) are the primary screening tools that are currently being used to assess cognitive impairment.[21] Even though these measures have been known for their screening reliability, how well these tests may screen cognitive impairment in those with a hearing impairment is not elucidated. In addition to the test instructions, 10 points of the maximum possible MoCA score of 30 and 4 of the maximum possible MMSE score of 30 that need to be heard for the participant to attend to the task.[21] Dupuis et al[21] reported that even a mild-moderate hearing loss can significantly affect performance on MoCA. When MoCA scores were re-analysed by removing test items that heavily relied on audition,

compared to the original scoring procedure, the number of hearing impaired participants who scored cognitively normal increased.[21] Deal et al.[5] reported a significant difference in memory scores of both moderate/severe and mild hearing loss participants after test items that comprised of only auditory items were removed from the cognitive domain summary scores. By accounting for the hearing impairment of older adults during cognitive assessments this could possibly reduce the overestimation of cognitive impairment.[21]

An analysis of the cognitive assessments utilised in studies that have thus far investigated the link between cognition and hearing loss suggest that most of these studies have used verbally loaded (i.e. the materials are presented orally-aurally) test materials that rely on audition.[4,7,22] Hill-Briggs et al[23] recommended not using verbally loaded cognitive assessments with those who have a severe hearing impairment as the severe hearing impairment would impede one's ability to fully and accurately access relevant information. Therefore, it is essential to use cognitive assessments that accommodates hearing impairment. The above mentioned findings forms a basis that non-verbal cognitive test materials should be used when assessing cognitive functions of hearing impaired participants.

Our prospective case-controlled study investigated the association between untreated hearing loss and cognitive functions of older adults using a battery of non-verbal, non-auditory cognitive assessments. We selected a computerised non-verbal cognitive test battery as hearing loss is not considered a factor that impacts performance of visually presented cognitive assessments.[18] In addition, association between untreated hearing loss and psychological functions such as anxiety, depression and stress were examined.

Methods:

Ethics approval for this study was obtained from The University of Western Australia-Human Research Ethics Committee (RA/4/1/7368). All procedures were undertaken in accordance with this approval.

Participants: Participants were recruited through radio and newspaper advertisements and the Ear Science Institute Australia Hearing Implant Centre. A total of 119 Australian English speakers or native English speakers who have been speaking Australian English for 10 years or longer, aged between 45-85 years with bilateral symmetrical pure-tone audiometric thresholds were recruited for the study. Those who did not meet the above-mentioned criteria were excluded. The study sample consisted of total of 54 males [mean (M) = 66.33 ± 10.50 years] and 65 females (M = 61.51 ± 11.46 years). Out of 119 participants recruited for the study, based on average, bilateral air conduction thresholds across 500 Hz - 4 kHz, 47 had normal hearing (NH) < 25 dBHL, 51 had mild-moderate hearing loss (MMH) = 26dBHL and 55 dBHL and 21 had moderately-severe to profound hearing loss (MSPH) > 55 dBHL (Table 1).

Table 1. Participant demographic details

Participant group	Number (gender)	Age (mean ± SD) years	NART-R score[†] (mean ± SD)
NH[‡]	47 (19 Males & 28 Females)	58.04 ± 9.15	111.79 ± 7.65
MMH[§]	51 (25 Males & 26 Females)	67.52 ± 10.26	110.92 ± 8.35
MSPH[ǀ]	21 (10 Males & 11 Females)	67.40 ± 12.90	106.55 ± 7.11

[†] National Adult Reading test- Revised[25].
[‡]Normal Hearing; [§]Mild-Moderate Hearing Loss; [ǀ]Moderately-Severe to Profound Hearing Loss.

Materials and Procedure: The assessment materials included measures of hearing ability, cognition and psychological status.

Hearing Assessment: included a pure-tone audiometric assessment (MIDIMATE 602 Audiometer, GN Otometrics Ltd, Sydney). Bilateral air conduction thresholds between 0.5- 8 kHz and bone conduction thresholds between 0.5- 4 kHz were obtained through standard audiometric assessment conducted by a qualified audiologist in a sound proof booth.

Cognitive Assessment: Prior to completing CANTAB[24] assessment, participants were asked to read aloud a list of 50 words from the NART-R[25] test while the researcher recorded the number of errors made by the participant. Verbal intelligence quotient (VIQ) was calculated based on NART-R error score and VIQ score was entered into the CANATB[24] software along with participant demographic details. The cognitive function of participants was assessed using computerized the Cambridge Neuropsychological Test Automated Battery.[24] The CANTAB software was installed on a computer with an integrated touch screen (Dell, Inspiron One, with Windows 8.1 platform). Participants completed the following modules of the CANTAB test battery:

1. Motor Screening Task (MOT): MOT is a brief introductory exercise to familiarize participants with the touch screen interface.[24] MOT identifies difficulties in vision, comprehension and hand movement of the participant. Those who could not complete the MOT module due to visual impairment, inability to comprehend test instructions or inability to attend to the task due to dexterity problems were going to be eliminated from the study.

2. Attention Switching task (AST): AST is a test of executive functioning and provides a measure of cued attentional set shifting.[24] AST is based on the Stroop test and relies heavily on the functions of the anterior right hemisphere and medial frontal structures.[26] During each trial, an arrow appears either on the right or on the left hand side of the screen and which will

point, independently, in the right or left direction. In addition the word 'Direction' or 'Side' will appear at the top of the screen. The participant's task is to follow the instructions that appear on the top of the screen and make a decision about the direction of the arrow, or the side of the screen on which the arrow appears. This is recorded by the participant selecting either 'Left' or 'Right' on the touch screen. A percentage of correct trials were calculated as the outcome measure.

3. Delayed Matching to Sample (DMS): This task assesses participants' ability to recognize complex visual patterns at different time intervals.[24] This test is primarily sensitive to medial temporal lobe dysfunction. The participant is shown a complex visual pattern (the sample) and four response patterns. The participant's task is to identify the response pattern that is identical to the sample pattern. Response patterns will be shown simultaneously with the sample pattern or after a brief delay of (0, 4, or 12 seconds). Percentage of correct responses selected by the participant was calculated for this task.

4. Paired Associates Learning (PAL): PAL is a recall test of memory which assesses episodic visuospatial memory, learning and association ability.[24] PAL is primarily sensitive to the changes in medial temporal lobe functioning.[24] In this task, six white boxes are displayed on a computer screen. These briefly reveal a pattern which varies in shape and colour. The participant's task is to remember the pattern revealed and match it to the pattern that apperas in the middle of the screen by touching the box that contains the correct response. Task is made progressively difficult by presenting 1, 2, 3, 6 and 8 patterns to the participant. The outcome measure included 'PAL Total errors (adjusted)'. It reports the total number of errors across all assessed problems and all stages, with an adjustment for each stage not attempted due to previous failure.

5. Verbal Recognition Memory (VRM): VRM assesses immediate and delayed memory of verbal information under free recall and forced recognition conditions.[24] In this task, patricipants is shown a list of 12 words and asked (i) repeat aloud as many words as possible immediately following the presentation (immediate free-recall) of all 12 words, (ii) recognise the original words from a list of 24 words presented on the screen that contains 12 original and 12 distractor words (immediate recognition) and (iii) recognise the original words from a list of 24 words presented on the screen that contains 12 original and 12 new distractor words, after 20 minutes delay (delayed recall). The following outcome measures are calculated: immediate free recall total correct responses, immediate recognition - total correct responses and delayed recognition - total correct scores.

6. Spatial Working Memory (SWM): measures the retention and manipulation of visuospatial information in areas such as non-verbal working memory, visuospatial working memory and strategy use.[24] SWM measures heuristic strategy and sensitive to frontal lobe dysfunction.[24] Participant's task was to loacte tokens hidden in increasing number of boxes (3, 4, 6 and 8). Each box conatined only one token per sequence. Searching a box more than once during a sequence results in a 'within search error' and revisiting a box in which a token has been found before incurrs a 'between search error'. A 'strategy' score, calculated for the more difficult six and eight box levels, represented the use of an efficient strategy based on predetermined sequence. Poor use of strategy is reflected in higher strategy scores and vice versa. SWM within errors, between errors and a strategy scores were calculated for the purpose of this study.

Assessment of depression, anxiety, and stress: The Depression Anxiety Stress Scales: DASS-21[27] was used to measure the current severity (past seven days) of a range of symptoms common to depression, stress and anxiety. It uses a 4-point combined severity/frequency scale to rate the extent to which the participant has experienced each question/statement over

the past week. Each test item is scored from 0 (never –did not apply to me at all over the last week) to 3 (almost always -applied to me very much most of the time over the past week). Scores for Depression, Anxiety, and Stress were separately calculated by summing the scores for the relevant items and the final score for each sub-category was multiplied by two (x2) as per the questionnaire scoring instructions .

Statistical analysis: All statistical analyses were performed using SPSS, version 23 (SPSS Inc., Chicago, Illinois, USA). Hierarchical multiple regression analysis was used to examine the association between untreated hearing loss and cognitive functions and anxiety, stress and depression score. To examine the relationship between cognition and hearing loss, we have entered age, gender, and NART-R as our demographic factors in the first step. In the next two steps we have included the depression and better ear average 500 Hz- 4kHz hearing thresholds (BE 4PTA), respectively. For the regression analysis, BE 4PTA was considered as a continuous variable. The CANTAB sub-module scores have been entered as dependant variables. To examine the relationship between hearing loss and psychological functions, we have entered age-gender and NART-R scores as the demographic variables in the first step and BE 4PTA in the next step. Total scores for depression, anxiety and stress were individually entered as the dependant variables.

To examine the relationship between the severity of hearing loss based on three participant groups (NH, MMH & MSPH) and cognition, a series of analysis of covariance (ANCOVA, univariate) was conducted. For this analysis gender and hearing loss groups (NH, MMH & MSPH)) were considered as the fixed factors and age, NART-R and depression as the covariates. Multiple comparisons were adjusted using Bonferroni corrections. To examine the relationship between the severity of hearing loss (NH, MMH & MSPH) and psychological functions, a series of analysis of covariance (ANCOVA, univariate) was conducted. For this analysis gender and hearing loss groups ((NH, MMH &

MSPH) were considered as fixed-factors and age and NART-R as the covariates. Multiple comparisons were adjusted using Bonferroni corrections.

Results:

Cognitive function and hearing

A hierarchical multi-regression analysis results revealed that BE 4PTA significantly predicted PAL total errors ($p < .05$), SWM between error scores ($p < .001$), SWM within errors ($p < .001$) and strategy ($p = .03$). Result are summarised in Table 2.

Psychological functions and hearing

A hierarchical multi-regression analysis results revealed that age, NART-R and gender did not significantly predict results of any of the psychological functions. BE 4PTA statistically significantly predicted the depression, anxiety and stress. Results are summarised in Table 3.

Group difference- Cognitive functions

The relationship between the severity of hearing loss (NH, MMH & MSPH) and cognition was examined by using a series of analysis of covariance (ANCOVA, univariate) tests. Mean and standard deviation scores obtained by each participant group for each of the CANTAB modules are summarised in Table 1 (supplementary material). The ANCOVA post-hoc analysis results are summarised in Table 4.

Group difference-Psychological functions

The relationship between the severity of hearing loss (NH, MMH & MSPH) and psychological functions, was examined using a series of analysis of covariance (ANCOVA,

univariate) tests. Mean and standard deviation scores obtained by each participant group for depression, anxiety and stress are summarised in Table 2 (supplementary material). The ANCOVA post-hoc analysis results are summarised in Table 5.

Table 2. Hierarchical multi-regression analysis scores for CANTAB test modules received by participants of this study.

Dependant variables	**Independent variables**	**R^2**	**Adjusted R^2**	**F**	**B**	**β**	**Sig.**	**95% Confidence Interval for B**	
								Lower bound	**Upper Bound**
AST[§] percent correct	Age	30	0.28	F(5, 113) = 9.81, p < .001	-0.32	-0.42	0.00**	-0.45	-0.19
	NART-R[†]				0.33	0.30	0.00**	0.15	0.50
	Gender				-1.83	-0.13	0.19	-4.63	0.95
	Depression				-0.01	-0.01	0.95	-0.34	0.31
	BE 4PTA[‡]				-0.06	-0.16	0.18	-3.87	0.74
DMS[‖] percent correct	Age	0.31	0.28	F(5, 113) = 10.25, p < .001	-0.34	-0.37	0.00**	-0.50	-0.16
	NART-R				0.23	0.17	0.04*	0.01	0.44
	Gender				4.02	0.19	0.03*	0.66	7.29
	Depression				-0.36	-0.16	0.04*	-0.77	0.04
	BE 4PTA				-1.15	-0.08	0.66	-3.90	1.60
PAL[¶] total errors	Age	0.39	0.37	F(5, 113) = 14.65, p < .001	1.47	0.45	0.00**	0.99	1.96
	NART-R				-0.31	-0.07	0.34	-0.95	0.35
	Gender				-7.08	-0.10	0.18	-17.71	3.54
	Depression				0.13	0.01	0.84	-1.15	1.41
	BE 4PTA				11.79	0.24	0.01*	3.00	20.58
	Age	0.29	0.26		-0.06	-0.35	0.00**	-0.09	-0.03

VRM[#] free recall-immediate	NART-R			F(5, 113) = 9.25, p < .001	0.06	0.24	0.01 *	0.01	0.09
	Gender				0.93	0.23	0.01 *	0.30	1.57
	Depression				-0.01	-0.01	0.83	-0.08	0.60
	BE 4PTA				-0.04	-0.01	0.86	-0.57	0.48
VRM recognition - immediate	Age	0.26	0.22	F(5, 113) = 7.60, p < .001	-0.02	-0.28	0.01 *	-0.06	-0.01
	NART-R				0.02	0.15	0.07	0.00	0.05
	Gender				0.80	0.30	0.01 *	0.36	1.26
	Depression				-0.01	-0.01	0.86	-0.06	0.05
	BE 4PTA				-0.02	-0.01	0.90	-0.39	0.35
VRM recognition -delayed	Age	0.04	-0.02	F(5, 113) = 0.89, p =.48	-0.03	-0.13	0.21	-0.08	0.02
	NART-R				0.02	0.07	0.48	-0.04	0.08
	Gender				0.54	0.11	0.27	-0.43	1.52
	Depression				0.02	0.04	0.73	-0.10	0.14
	BE 4PTA				0.08	0.02	0.84	-0.72	0.89
SWM[††] between errors	Age	0.45	0.42	F(5, 113) = 18.25, p < .001	0.87	0.46	0.00 **	0.58	1.17
	NART-R				-0.43	-0.16	0.03	-0.82	-0.04
	Gender				1.30	0.03	0.68	-4.94	7.55
	Depression				-0.05	-0.01	0.90	-0.81	0.71
	BE 4PTA				9.90	0.33	0.00 **	4.64	15.15
SWM within errors	Age	0.39	0.36	F(5, 113) = 14.59, p < .001	0.89	0.44	0.00 **	0.56	1.22
	NART-R				-0.46	-0.16	0.04 *	-0.89	-0.02
	Gender				2.33	0.05	0.50	-4.53	9.20
	Depression				-0.05	-0.01	0.91	-0.88	0.79
	BE 4PTA				9.17	0.29	0.00 **	3.40	14.95
SWM strategy	Age	0.32	0.29		0.23	-0.18	0.03 *	0.13	0.34

NART-R		-0.15	0.20	0.01*	-0.29	-0.02
Gender	F(5, 113) = 9.36, p < .001	2.76	-0.12	0.19	0.59	4.94
Depression		-0.18	0.30	0.00**	-0.44	0.09
BE 4PTA		2.85	0.21	0.03*	1.05	4.65

Table 3. Hierarchical multi-regression analysis results for depression, anxiety and stress scores.

Dependant variables	Independent variables	B	β	Sig.	95% Confidence Interval for B	
					Lower bound	Upper Bound
Depression	Age	-0.04	-0.11	0.22	-0.12	0.03
	NART-R†	-0.02	-0.03	0.70	-0.12	0.08
	Gender	0.01	0.00	0.99	-1.53	1.55
	BE 4PTA‡	3.30	0.52	0.00**	2.19	4.42
Anxiety	Age	-0.03	-0.07	0.47	-0.11	0.05
	NART-R	-0.04	-0.07	0.41	-0.15	0.06
	Gender	0.79	0.08	0.35	-0.88	2.46
	BE 4PTA	3.00	0.45	0.00	1.79	4.21
Stress	Age	-0.17	-0.29	0.00**	-0.27	-0.06
	NART-R	0.13	0.16	0.07	-0.01	0.26
	Gender	0.17	0.01	0.88	-2.01	2.36
	BE 4PTA	4.29	0.49	0.00**	2.70	5.87

† NART-R: National Adult Reading Test-Revised score [25]; ‡ BE 4PTA: average, 4 frequency (500 Hz, 1 kHz, 2 kHz & 4 kHz) pure-tone air conduction hearing thresholds of the better ear; significant values are marked with *P < .05 & **P <.001.

Table 4. Analysis of covariance post-hoc analysis results for all three participant groups for CANTAB sub-modules

Dependent Variable	Participant group		Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
AST[‖] percent correct trials	NH[†]	MMH	1.70	0.28	-1.28	6.97
		MSPH	2.42	1.00	-3.68	8.08
	MMH[‡]	NH	1.70	0.28	-7.00	1.28
		MSPH	2.09	1.00	-5.74	4.42
	MSPH[§]	NH	2.42	1.00	-8.08	3.68
		MMH	2.09	1.00	-4.42	5.74
DMS[¶] percent correct	NH	MMH	2.04	0.69	-2.51	7.43
		MSPH	2.91	1.00	-4.42	9.73
	MMH	NH	2.04	0.69	-7.43	2.51
		MSPH	2.51	1.00	-5.91	6.31
	MSPH	NH	2.91	1.00	-9.73	4.42
		MMH	2.51	1.00	-6.30	5.91
PAL[††] total errors (adjusted)	NH	MMH	6.35	1.00	-20.38	9.22
		MSPH	9.03	0.00**	-46.27	-8.45
	MMH	NH	6.35	1.00	-9.22	20.38
		MSPH	7.80	0.01*	-39.40	-4.16
	MSPH	NH	9.03	0.00**	8.45	46.27
		MMH	7.80	0.01*	4.16	39.40
VRM[#] free recall - total correct [immediate]	NH	MMH	0.38	1.00	-0.90	0.94
		MSPH	0.56	1.00	-1.03	1.43
	MMH	NH	0.39	1.00	-0.94	0.97
		MSPH	0.48	1.00	-1.10	1.26
	MSPH	NH	0.56	1.00	-1.43	1.30
		MMH	0.48	1.00	-1.22	1.10
VRM Recognition - total correct [immediate]	NH	MMH	0.26	1.00	-0.67	0.67
		MSPH	0.39	1.00	-0.88	1.02
	MMH	NH	0.27	1.00	-0.67	0.67
		MSPH	0.34	1.00	-0.75	0.89
	MSPH	NH	0.39	1.00	-1.02	0.88
		MMH	0.33	1.00	-0.89	0.75
VRM recognition delayed	NH	MMH	0.59	1.00	-2.00	0.89
		MSPH	0.84	1.00	-2.08	2.00
	MMH	NH	0.59	1.00	-0.89	2.00
		MSPH	0.73	1.00	-1.24	2.31

	MSPH	NH	0.84	1.00	-2.04	2.08
		MMH	0.73	1.00	-2.31	1.24
SWM[††] between errors	NH	MMH	3.81	0.00**	-25.30	-6.73
		MSPH	5.42	0.00**	-31.47	-5.08
	MMH	NH	3.82	0.00**	6.78	25.30
		MSPH	4.60	1.00	-13.46	8.94
	MSPH	NH	5.42	0.00**	5.08	31.47
		MMH	4.60	1.00	-8.94	13.46
SWM within errors	NH	MMH	4.20	0.00*	-25.71	-5.23
		MSPH	5.98	0.01*	-31.23	-2.21
	MMH	NH	4.20	0.00**	5.29	25.71
		MSPH	5.01	1.00	-13.52	11.10
	MSPH	NH	5.97	0.01*	2.21	31.23
		MMH	5.06	1.00	-11.01	13.54
SWM strategy	NH	MMH	1.33	0.01*	-6.97	-0.49
		MSPH	1.89	0.01*	-9.92	-0.70
	MMH	NH	1.33	0.01*	0.49	6.97
		MSPH	1.63	1.00	-5.56	2.40
	MSPH	NH	1.89	0.01*	0.70	9.92
		MMH	1.63	1.00	-2.40	5.56

[†] NH: Normal Hearing; [‡] MMH: Mild-Moderate Hearing Loss; [§] MMSPH: Moderately Severe Profound Hearing Loss; [ǀ] AST: Attention set switching; [¶] DMS: Delayed matching to sample; [††] PAL: Paired associates learning; [#] VRM: Verbal recognition memory; [††] SWM: Spatial working memory; significant values are marked with *P < .05 & **P <.001.

Table 5. Analysis of covariance post-hoc results for all three participant groups for depression, anxiety and stress.

Dependent Variable	Participant group		Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Depression	NH[†]	MMH	0.89	0.01*	-4.84	-0.49
		MSPH	1.14	0.00**	-9.77	-4.21
	MMH[‡]	NH	0.89	0.01*	0.49	4.84
		MSPH	1.06	0.00**	-6.91	-1.74
	MSPH[§]	NH	1.14	0.00**	4.21	9.77
		MMH	1.06	0.00*	1.74	6.91

Anxiety	NH	MMH	0.97	0.01*	-5.20	-0.47
		MSPH	1.24	0.00**	-9.33	-3.29
	MMH	NH	0.97	0.01*	0.47	5.20
		MSPH	1.16	0.01*	-6.29	-0.66
	MSPH	NH	1.24	0.00**	3.29	9.33
		MMH	1.16	0.01*	0.66	6.29
Stress	NH	MMH	1.28	0.01*	-7.08	-0.87
		MSPH	1.63	0.00**	-12.83	-4.89
	MMH	NH	1.28	0.01*	0.87	7.08
		MSPH	1.52	0.01*	-8.59	-1.19
	MSPH	NH	1.63	0.00**	4.89	12.83
		MMH	1.52	0.01*	1.19	8.59

†NH: Normal Hearing; ‡MMH: Mild-Moderate Hearing Loss; § MMSPH: Moderately Severe –Profound Hearing Loss: significant values are marked with *P < .05 & **P <.001.

Conclusions:

Hearing loss and Cognition:

The current study explored the association between hearing loss and a number of cognitive domains through a battery of non-verbal cognitive function tests. Results revealed that the sensorineural hearing loss significantly associated with poor performance on some of the cognitive domains, specifically, spatial working memory & episodic memory and learning.

Working memory functions in this study was measured using SWM tasks from the CANTAB test battery. Regression analysis data showed that BE 4PTA significantly associated with performance in SWM errors and strategy use. Current study data also revealed that number of SWM mean error scores increased as the severity of the hearing loss increased (Table 1 supplementary material). Another interesting finding of the current study is that MSPH group employed significantly poor strategy in SWM tasks compared to NH

participants (Table 1 supplementary material and Table 4). The SWM test is sensitive to non-verbal working memory impairment and executive functions and thus to the functions of prefrontal cortex.[28] Hearing impaired participants use storage and processing functions of the working memory capacity to compensate for distorted auditory input.[29] In keeping with previous studies, current results suggest that hearing loss could impede the ability to retain and manipulate the spatial working memory and executive functions. These studies suggest that when auditory perception is compromised as in difficult listening situations or due to hearing impairment, greater cognitive resources are utilised to process and interpret the incoming acoustic signal.[30] Divergence of these cognitive resources to hearing may deplete the cognitive reserve and negatively effects working memory.[30,31]

VRM assesses immediate and delayed memory of verbal information under free recall and forced recognition conditions.[24] Results of the current study failed to demonstrate any association between hearing thresholds and immediate recognition and recall or delayed recall conditions. To recapitulate, as the test materials for VRM task were presented visually, hearing status had no impact on participants' ability to perform the task. Based on these results it is posited that the non-verbal recall and recognition tasks are not affected by postlingual hearing impairment.

Our results are consistent with Ronnberg et al[32] findings that ageing and hearing loss significantly impairs the episodic visual memory. The PAL task used in this test battery measured the participant's ability to match stimulus to location, episodic visuospatial memory, learning and association ability.[24] Both hearing impaired groups showed higher mean error scores compared to NH participants (Table 1 supplementary material). Junkkila et al[33] used CANTAB-PAL total errors adjusted to differentiate between healthy ageing, amnestic mild cognitive impairment (aMCI) and Alzheimer's disease (AD). Findings revealed that a cut-off of 42 and 71 errors adjusted was found to best differentiate between

healthy ageing and aMCI and aMCI and AD patients, respectively.[33] Using the cut-off criteria reported by Junkkila et al[33] one can argue that both MMH & MSPH participants of the current study meet the cut-off criteria for aMCI. That is, even a mild hearing impairment could have a negative effect on cognitive functions.

Hearing loss and Psychological findings:

Severely hearing impaired older listeners find everyday listening to be an effortful and stressful task.[34] Use of compensatory executive processes to retrieve information from the long-term memory by hearing impaired listeners could result in increased effort and cognitive load.[35] Our data confirm that untreated hearing loss is associated with risk of depression, anxiety and stress and elevation of hearing thresholds may elevate the risk of developing these symptoms (Tables 2 & 5). Further, depression is known to significantly reduce the quality of life of older adults.[36] Negative rumination associated with depression decreases working memory functions,[37] which was observed in the current study with hearing impaired participants performing poorly on SWM task. Further, depression scores significantly ($P = 0.04$) predicted the performance on DMS task, which is a measure of visual working memory and sensitive to the damages in the hippocampus.[38] Hickie et al[39] reported a decrease in hippocampus volume in participants diagnosed with depression. In addition, depression is also associated with impaired attentional resources, all elements of working memory and executive dysfunction.[40] It is proposed that hearing loss could lead to increased risk of depression, anxiety and stress and draw on working memory resources leading to recruitment of compensatory executive processes to attend to daily listening needs. As compensatory executive processes are already recruited to retrieve information from long-term memory due to compromised working memory functions resulted from hearing loss,[41] this may lead to

further cognitive impairment. Of note, depression increases the risk of developing future pathological cognitive impairment and dementia.[42]

Our findings further reinforce previous findings that peripheral hearing loss is associated with cognitive impairment and poor psychological functions. As previously explained in the introduction, given the nature of complex relationship between hearing loss, psychological functions and cognition, it is difficult to ascertain a causal relationship between hearing loss and cognitive impairment. Moreover, recent studies have considered ARHL as an important frailty marker in older adults.[43,44] Several factors related to physical frailty including inflammatory markers and vascular detriments are also been linked to cognitive impairment and age- related hearing loss.[45-47] Therefore, further randomised control studies or large population based studies on vascular detriments associated with ARHL, frailty and cognitive impairment could help better understand the underpinning causal mechanisms.[43,45]

Summary and Clinical Implications:

In summary, the impaired cognitive functions are observed mainly in the areas of working memory and paired associate learning tasks of hearing impaired participants. As these participants express difficulty in attending to speech stimuli, it may be more beneficial to use non- verbal cognitive assessments as opposed to verbal test material when assessing older adults with a hearing loss.

Further, BE 4PTA also associated with the depression, anxiety and stress scores of the participants of this study. Based on the current findings, MSPH participants suffer from high-levels of anxiety, stress and depression. This has clinical implications specifically for hearing health care professionals and these factors are important to consider when counselling potential hearing aid or cochlear implant candidates.

Limitations of the study:

One of the limitations of the study is that participants were not clinically assessed to exclude the potential for pathological cognitive impairment. Due to the small sample size of the study, the results should be treated as such. However, our results warrant longitudinal studies to examine the association between age-related hearing loss and cognitive impairment over time.

Conflict of interest: DMPJ, PLF and RHE report no conflicts of interest to declare. RNM is the founder and chief scientific officer of the biotech company, Alzhyme. HRS has, and continues to receive remuneration from activities with Pfizer and Takeda pharmaceuticals.

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Supplementary material

Table 1. Mean and standard deviation values for the all three participant groups for CANTAB sub-modules. Standard deviation values are reported within brackets.

Participant group	AST[|] percent correct trials	DMS[¶] percent correct	VRM[#] free recall total correct [immediate]	VRM recognition total correct [immediate]	VRM recognition delayed	PAL[††] total errors (adjusted)	SWM[‡‡] between errors	SWM within errors	SWM strategy
NH[†]	96.79 (4.93)	90.98 (6.38)	8.17 (1.95)	23.07 (1.10)	22.57 (3.73)	25.11 (23.69)	19.83 (13.06)	20.63 (13.30)	39.87 (6.53)
MMH[‡]	90.69 (9.77)	84.03 (11.70)	7.37 (1.95)	22.63 (1.39)	22.70 (1.39)	47.47 (35.91)	43.98 (21.68)	39.87 (23.77)	45.10 (5.79)
MSPH[§]	89.94 (9.27)	81.74 (10.51)	7.00 (1.76)	22.19 (1.36)	22.19 (1.36)	68.14 (34.73)	46.86 (16.76)	44.47 (6.53)	46.29 (6.02)

[†]NH: Normal Hearing; [‡]MMH: Mild-Moderate Hearing Loss; [§]MSPH: Moderately-Severe to Profound Hearing Loss; [|]Attention set switching; [¶]Delayed matching to sample; [#]Verbal recognition memory; [††]Paired associate learning; [‡‡]Spatial working memory

Supplementary material

Table 2. Mean and standard deviation values for depression, anxiety and stress obtained by all three participant groups. Standard deviation scores are reported within brackets.

Participant group	Depression	Anxiety	Stress
NH[†]	2.2 (2.1)	2.4 (2.6)	6.7 (5.2)
MMH[‡]	4.4 (4.1)	4.8 (5.3)	9.0 (6.7)
MSPH[§]	8.8 (6.3)	8.4 (5.1)	13.3 (5.8)

[†]NH: Normal Hearing; [‡]MMH: Mild-Moderate Hearing Loss; [§]MSPH: Moderately-Severe to Profound Hearing Loss.