Longitudinal relationships between hearing aid use and cognitive function in older Americans

DOI:

[10.1111/jgs.15363](https://doi.org/10.1111/jgs.15363)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Maharani, A., Dawes, P., Nazroo, J. Y., Tampubolon, G., Pendleton, N., & Leroi, I. (2018). Longitudinal relationships between hearing aid use and cognitive function in older Americans. *Journal of the American Geriatrics Society*, 66(6), 1130-1136. <https://doi.org/10.1111/jgs.15363>

Published in:

Journal of the American Geriatrics Society

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

**Journal of the
American Geriatrics Society**

**Longitudinal relationships between hearing aid use and
cognitive function in older Americans**

Journal:	<i>Journal of the American Geriatrics Society</i>
Manuscript ID	JAGS-0091-CI-Jan-18.R1
Wiley - Manuscript type:	Clinical Investigation
Date Submitted by the Author:	n/a
Complete List of Authors:	Maharani, Asri; University of Manchester, Division of Neuroscience and Experimental Psychology Dawes, Piers; University of Manchester, Division of Human Communication, Development & Hearing Nazroo, James; University of Manchester, Sociology and Cathie Marsh Institute for Social Research Tampubolon, Gindo; University of Manchester, Sociology and Cathie Marsh Institute for Social Research Pendleton, Neil; The University of Manchester, Division of Neuroscience and Experimental Psychology, School of Biological Sciences
Key Words:	hearing aid use, cognition, longitudinal analysis

Title : Longitudinal relationships between hearing aid use and cognitive function in older Americans

Short running title : Hearing aid use and cognitive function in older adults

Author : Asri Maharani, PhD,¹ Piers Dawes, PhD,² James Nazroo, Professor,³ Gindo Tampubolon, PhD,³ and Neil Pendleton, Professor,¹ on behalf of the Sense-Cog WP1 group

Corresponding author: Asri Maharani

Address: Humanities Bridgeford Street Building G21, Oxford Road, Manchester M13 9PL, United Kingdom

Telephone: +44 161 57025

Email address: asri.maharani@manchester.ac.uk

Author affiliation and qualification:

1 Division of Neuroscience and Experimental Psychology, School of Biological Sciences, Faculty of Biology, Medicine and Health, University of Manchester, Manchester Academic Health Science Centre, Manchester M13 9PL, United Kingdom

2 Division of Human Communication, Development & Hearing, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

3 Sociology and Cathie Marsh Institute for Social Research, University of Manchester Humanities Bridgeford Street Building, Oxford Road, Manchester M13 9PL, United Kingdom

21 **Impact statement:**

22 We certify that this work is novel of recent novel clinical research. This manuscript is
23 important for the literature as it showed for the first time that cognitive decline at different
24 rate before and after the beginning of hearing aid use which holds an important public health
25 implication to improve cognitive health and prevent dementia among older people.

26 **Conflict of interest:**

27 The authors have no financial or any other kind of personal conflicts with this paper.

28 **Authors Contributions:**

29 AM, GT, JN, PD and NP made substantial contributions to the study design. AM analysed
30 the data. GT, JN, PD and NP contributed to the statistical design of the study. AM, GT, JN,
31 PD and NP contributed to the interpretation of the data and wrote each draft of the
32 manuscript. All authors critically reviewed and contributed significantly to the intellectual
33 content of the manuscript. AM had full access to all the data in the study and all authors had
34 final responsibility for the decision to submit for publication.

35 **Acknowledgement:**

36 The Sense-Cog WP1 group are Geir Bertelsen^{1,2}, Suzanne Cosh³, Audrey Cougnard-
37 Grégoire³, Cécile Delcourt³, Fofi Constantinidou⁴, Catherine Helmer³, M. Arfan Ikram^{5,6},
38 Caroline CW Klaver^{5,7}, Iracema Leroi⁸, Magda Meester-Smor^{5,7}, Unal Mutlu^{5,7}, Virginie
39 Nael^{3,9,10}, Henrik Schirmer¹¹, Henning Tiemeier^{5,12}, Therese von Hanno^{13,14}.

40 1: UiT The Arctic University of Norway, Department of Community Medicine, Faculty of
41 Health Sciences, N-9037 Tromsø, Norway

42 2: University Hospital of North Norway, Department of Ophthalmology, N-9038 Tromsø,
43 Norway

- 3: Univ. Bordeaux, Inserm, Bordeaux Population Health Research Center, team LEHA, UMR 1219, F-33000 Bordeaux, France
- 4: University of Cyprus, Department of Psychology & Center for Applied Neuroscience, Nicosia, Cyprus
- 5: Erasmus Medical Centre, Department of Epidemiology, Rotterdam, The Netherlands
- 6: Erasmus Medical Centre, Departments of Neurology and Radiology, Rotterdam, The Netherlands
- 7: Erasmus Medical Centre, Department of Ophthalmology, Rotterdam, The Netherlands
- 8: University of Manchester, Division of Neuroscience and Experimental Psychology, School of Biological Sciences, Manchester, UK
- 9: Sorbonne University, UMPC University of Paris 06, INSERM, CNRS, Vision Institute, F-75012 Paris, France
- 10: R&D Life and Vision Science, Essilor International, F-75012 Paris, France
- 11: UiT-The Arctic University of Norway, Department of Clinical Medicine, Cardiovascular research Group-UNN, N-9037 Tromsø, Norway
- 12: Erasmus Medical Centre, Department of Psychiatry, Rotterdam, The Netherlands
- 13: UiT-The Arctic University of Norway, Department of Clinical Medicine, Faculty of Health Sciences, N-9037 Tromsø, Norway
- 14: Nordland Hospital, Department of Ophthalmology, N-8092 Bodø, Norway

44 **Funding source:**

45 This work was supported by SENSE-Cog project. This project has received funding from the
46 European Union’s Horizon 2020 research and innovation programme under grant agreement
47 No 668648.

48 **Abstract word counts:** 195 words

49 **Main document word counts:** 2,999 words

50 **Number of tables:** 2 tables

51 **Number of figures:** 2 figures

52

For Review Only

53 **Abstract**

54 **Objective:** To test whether hearing aid use alters cognitive trajectories in older adults.

55 **Design, setting, and participants:** Data were drawn from the Health and Retirement Study
56 (HRS), a US population-based longitudinal cohort study with cognitive performance
57 measured repeatedly every 2 years over 18 years (1996-2014). This study included 1,586
58 adults aged 50 and older who who took part in a minimum of three waves of the HRS and
59 who used hearing aids for the first time between Wave 4 and Wave 11.

60 **Measurements:** Cognitive outcomes were based on episodic memory scores determined by
61 the sum of immediate and delayed recall of 10 words.

62 **Results:** Hearing aid use was positively associated with episodic memory scores ($\beta=1.24$,
63 $p<0.001$). The decline in episodic memory scores was slower after ($\beta=-0.02$, $p<0.001$) than
64 before using hearing aids ($\beta=-0.1$, $p<0.001$). These results were robust to adjustment for
65 multiple confounders and and to attrition as accounted for with joint model.

66 **Conclusions:** Hearing aids may have a mitigating impact on trajectories of cognitive decline
67 in later life. Providing hearing aids or other rehabilitative services for hearing impairment
68 much earlier in the course of hearing impairment may stem the worldwide rise of dementia.

69 Key words: Hearing aid use, cognition, longitudinal analysis

70

71

72

73 **Introduction**

74 Neurodegenerative dementias such as Alzheimer disease are a major health problem in the
75 worldwide aging population. The number of people living with dementia is projected to
76 increase by 57% in the next two decades, from 46 million in 2015 to 72 million in 2050.^{1,2}
77 This rising global prevalence, combined with the lack of effective curative treatment, has
78 rendered the prevention of dementia a public health concern.

79 A recent study by Livingston et al. (2017) showed that intervention on risk factors not
80 including hypertension might prevent 35% of dementia cases³ and that the strongest midlife
81 risk factor for dementia is hearing impairment. It showed that approximately 9% of dementia
82 cases are attributable to hearing loss in midlife. Our previous study, using three longitudinal
83 surveys on ageing health, showed that individuals with hearing and visual impairments had
84 lower episodic memory scores and a more adverse trajectory of decline in memory scores
85 with age than those with no impairment.⁴ The relationship between of hearing impairment
86 and lower cognitive ability in later life has also been reported by numerous cross-sectional⁵⁻⁷
87 and longitudinal studies.⁸⁻¹⁰ As hearing impairment is prevalent, alleviating it might delay the
88 point that older adults cross the critical threshold of impairment into dementia.

89 Hearing impairment as a risk factor for dementia is not only greater than other individual
90 midlife risks but is also relevant to many individuals because of its relatively high prevalence
91 in middle and old age. At least 10% of individuals aged 40 to 69 years show some degree of
92 measurable hearing impairment¹¹ and that this proportion increases with age. The prevalence
93 of hearing impairment increases to 30% of individuals over the age of 65, and between 70%
94 and 90% individuals over the age of 85 experience some hearing loss.^{12,13} Although hearing
95 impairment is highly prevalent, it remains largely under treated.¹⁴ Only 1 in 7 adults aged 50+

96 with hearing impairment use hearing aids, and this figure declines to fewer than 1 in 20 for
97 working-aged adults (50-59 years old).¹²

98 The effect of hearing aid interventions on cognitive function remains poorly understood.
99 Cross-sectional studies from the US⁵ and the UK¹⁵ have reported that hearing aid use is
100 associated with better cognitive scores. In contrast, a study using a cross-sectional cohort of
101 the Baltimore Longitudinal Study of Aging found no significant relationship between hearing
102 aid use and cognitive ability.¹⁶ The insignificant effect of hearing aid use on cognitive
103 function was also shown in several small longitudinal studies of short duration.^{8-10,17,18}

104 We used an 18-year follow-up of the Health and Retirement Study cohort to assess the
105 consequences of hearing aid use on long-term age-related decline in episodic memory. Using
106 a self-reported measure of hearing aid use, the association between hearing impairment and
107 cognitive trajectories over 18 years was investigated in a community-based cohort of older
108 adults, and the trajectories of the individuals before using hearing aids were compared with
109 those after beginning to use hearing aids.

110 **Methods**

111 This study forms part of the SENSE-Cog multi-phase research programme, funded by the
112 European Union Horizon 2020 programme. SENSE-Cog aims to promote mental well-being
113 in older adults with sensory and cognitive impairments (<http://www.sense-cog.eu/>). The first
114 work package of this project aims to better understand the links among sensory, cognitive and
115 mental ill-health in older Europeans.

116

117

118 *Study population*

119 Our empirical analysis used the Health and Retirement Study (HRS) Waves 3 (1996-97) – 12
120 (2014-15). The HRS is an ongoing biennial investigation of US adults aged 50 years and
121 older that started in 1992. Sponsored by the National Institute of Aging and performed by the
122 Institute for Social Research at the University of Michigan, the HRS provides information on
123 demographic, socio-economic factors, and health.

124 We used Wave 3 and later of the HRS as the episodic memory scores using 10 words were
125 first available in the third wave. In our study, we restricted the sample to respondents age 50
126 years and older who responded to at least three waves of HRS, had no dementia in the
127 baseline, and used hearing aids for the first time between Waves 4 and 11. This gave a
128 sample of 2,040 individuals with the selection procedure as illustrated in Figure 1. We
129 describe the characteristics of the HRS core sample Waves 3-12, HRS core sample with at
130 least 3 observations and the final sample in Appendix 1. It shows that the average of age and
131 episodic memory scores of the core sample Waves 3-12 and final sample are similar.

132 *Measures*

133 The measures of cognitive ability in the HRS are the outcomes of simple tests, e.g. immediate
134 and delayed word recall (episodic memory), serial 7's test, backwards count starting from 20,
135 and date naming. In our analysis, we focused on one specific cognitive domain available in
136 all HRS waves used in this study: episodic memory. We were particularly interested in
137 episodic memory scores as they are more age-sensitive than other cognitive measures,¹⁹ do
138 not suffer from floor or ceiling effects,²⁰ have a common mechanism with cognitive control
139 variables¹⁴ and have a strong association with dementia. After allowing for established risk
140 factors for dementia, the odds ratio for dementia among members of the most advantaged

141 trajectory of episodic memory was more than five times lower than the reference
142 (disadvantaged) trajectory.²¹ In the HRS memory test, the interviewer read a list of 10 simple
143 nouns (e.g. book, child, hotel, etc.) once and the participants were asked to repeat those nouns
144 on two occasions: immediately after the words were read out (immediate recall) and after a
145 short interval (delayed recall). We calculated the episodic memory score as the sum of the
146 number of target words recalled at the immediate and the delayed recall phase (score ranging
147 from 0 to 20).²⁰

148 The timing of using hearing aids for the first time was based on self-definition through the
149 question: 'Do you ever wear a hearing aid?'. This question was posed to all respondents.
150 Based on the first time that respondents answered 'yes' to that question, we constructed a
151 dummy variable for hearing aid use (1 for the wave the first time the respondents used
152 hearing aids and after, 0 for the wave before the respondents used hearing aids). In total,
153 1,586 respondents used hearing aids for the first time during the fourteen-year period.

154 We included an extensive set of covariates as identified as risk factors for cognitive decline in
155 prior studies.²²⁻²⁵ Demographic covariates included age (in years) and sex (female as the
156 reference). Socio-economic covariates included education (less than high school, high school,
157 and college or higher), marital status (married or cohabiting, and not married) and wealth
158 (tertiles of income each wave). The lifestyle behaviour covariates included smoking, drinking
159 behaviour and physical activities. For smoking behaviour, respondents were classified as
160 non-smokers, past smokers and current smokers. We used the number of units per week to
161 measure drinking behaviour. Depressive symptoms were assessed with the 8-item Centre for
162 Epidemiological Studies Depression Scale.²⁶ Lastly, the number of comorbidities present was
163 included as the sum of several chronic diseases: heart disease, high blood pressure, lung
164 diseases, diabetes, stroke and cancer.

165 *Statistical analysis*

166 To model trajectories in episodic memory scores, we used hierarchical linear regression
167 analysis, which is designed to analyse longitudinal data. In this regression analysis, intra-
168 individual correlation is modelled using an individual specific random intercept and an
169 individual specific random slope. This analysis thus takes into account multiple observations
170 within individual and intra-individual correlation. In addition, it allows for adjustment of
171 potential confounding variables. We used a spline model with a knot at the beginning of
172 hearing aid use and assessed whether the slope before using hearing aid differed to the post-
173 hearing aid use slope. We included the hearing aid variable (coded as 1 after using hearing
174 aids and 0 prior to using hearing aids) and its interaction with the slope term (age) to test the
175 differences in cognitive trajectories before and after beginning to use hearing aids. The
176 associations between hearing aid use, age, age interaction with hearing aid use and episodic
177 memory scores were quantified in the first model. The demographic and socio-economic
178 determinants (age, gender, education, marital status, and wealth) and the variables
179 representing lifestyle behaviour, depression, and the number of chronic diseases present were
180 added in the final model.

181

182 *Sensitivity analysis*

183 For the first sensitivity analysis, we conducted two separated hierarchical linear regression
184 analyses with immediate and delayed word recall as the outcomes, while the second analysis
185 focused on attrition. The HRS, like other longitudinal studies on ageing is subject to attrition
186 in which respondents are prone to selective dropout due to death or poor health.^{27,28} Ignoring
187 those dropouts thus can result in bias in the analysis. We tested the sensitivity of our results

to attrition by using a joint model.²⁹ This resultant division into two parts, the growth curve model and the survival model, allowed the random effects to influence both episodic memory and attrition. Finally, we examined the role of gender in the association between hearing aid use and cognitive function by conducting separate analyses for females and males. The models were constructed using STATA 14 and Latent Gold 5.1.

Results

Table 1 shows the descriptive statistics of 2,040 HRS sample respondents who used hearing aids for the first time between Waves 4 and 11 at the first wave observed. The episodic memory score has a distribution close to the normal distribution with a sample mean of 10.4 and a standard deviation of 3.2. On average the respondents used hearing aids for the first time at 63 years old. The respondents were mostly males (61%) who had completed college or higher (45%) and were married (81%). The bivariate regression model (see Table 1, second and third columns) shows that age, depression score, and number of comorbidities have a negative and significant association with episodic memory scores. Being relatively well educated, drinking alcohol and engaging regularly in physical activities are positively associated with episodic memory scores.

The parameter estimates for the slope of episodic memory scores before and after beginning to use hearing aids in an initial model are presented in Table 2, left pane. Episodic memory declined significantly with the addition of age, but the rate of the decline was slower after beginning to use hearing aids ($\beta=-0.03$, $p<0.001$) than before ($\beta=-0.11$, $p<0.001$). The difference of the coefficient between those two slopes is 0.08 ($p<0.001$). In this model, hearing aid use was associated with higher memory scores ($\beta=2.13$, $p<0.001$). The association between hearing aid use and episodic memory scores remained significant when we included the risk factors in the second model ($\beta=1.24$, $p<0.001$). In this second model,

212 slopes for the decline of episodic memory scores remained steeper before beginning hearing
213 aid use ($\beta=-0.1, p<0.001$) than after ($\beta=-0.02, p<0.001$).

214 In the second model, several potential confounders and socio-demographic characteristics
215 showed significant associations with episodic memory scores. Being female, having attained
216 a higher level of education, having a higher income, drinking alcohol and engaging in regular
217 physical exercise were positively associated with episodic memory scores. Depression scores
218 and the presence of chronic diseases were associated with lower memory scores.

219 Figure 2 illustrates the change in episodic memory scores over time. The graph is centred at
220 the first time an individual used hearing aids. It is centred on the point of time at which as
221 individual used hearing aids for the first time. The lines to the left of the centre of the graph
222 shows the rate of change in episodic memory score in the years leading up to beginning
223 hearing aid use, and the lines to the right of the centre of the graph shows the rate of change
224 in episodic memory following the beginning of hearing aid use. The model is adjusted for
225 demographic, socio-economic, lifestyle behaviour and health status. For all individuals, there
226 is a decline in episodic memory leading up to hearing aid use. The episodic memory scores
227 continue to decline after beginning to use hearing aids; however, the rate of decline is less
228 steep.

229 The first sensitivity analysis shows that both the immediate and delayed word recall scores
230 declined significantly before using hearing aids and this significant decline diminished after
231 beginning to use hearing aids (see Appendix 2 and 3). For the second sensitivity analysis (see
232 Appendix 4 and 5), we found that the slope of cognitive decline before and after beginning to
233 use hearing aids in the joint model is similar to that in the growth curve model. These
234 findings indicate that our findings are robust. Our final sensitivity analysis showed that
235 although females performed better than males in the episodic memory test, they have similar

rate of cognitive decline before and after using hearing aids for the first time (see Appendix 6 and 7).

Discussion

Using a national representative survey spanning 18 years, our study shows a less steep decrease in episodic memory performance after beginning to use hearing aids compared to before using hearing aids. The reduced rate of decline following hearing aid use remained significant after we took attrition into account. From the theoretical point of view, this finding provides new evidence to disentangle the relationship between cognitive function and hearing impairment. In prior studies, two main hypotheses have been posited to explain this relationship. The ‘common cause hypothesis’ argues that hearing impairment and cognitive decline share common age-related change factors such as the degeneration of the central nervous system.^{30,31} The ‘cascade hypothesis’, on the other hand, claims that prolonged reduction of hearing function leads to insufficient stimulation, which may in turn cause cognitive decline in later life.^{8,15,32,33} These hypotheses lead to different predictions regarding on the impact of hearing aid use on cognition. According to the common cause hypotheses, hearing aids may not affect cognition given that degeneration of central nervous system affects regardless of the maintenance of good hearing function.

The slower rate of cognitive decline among those with hearing impairment who have begun hearing aid use thus supports the cascade hypothesis. According to this hypothesis, hearing aids may allow better hearing input and delay cognitive decline through either preventing the adverse effects of auditory deprivation or facilitating lower levels of depression symptoms, increased social engagement, and higher self-efficacy that have a positive impact on cognitive function. Prior studies have reported that hearing aid users experienced less anxiety and depression^{34,35} and better quality of social engagement after beginning to use hearing

aids; both lower social engagement and depression are independently associated with cognitive decline.³⁷⁻³⁹ Another mechanism through which hearing aids may reduce the rate of cognitive decline is that they may enhance self-efficacy, the belief in one's own ability to accomplish tasks or succeed in specific situations,⁴⁰ which in turn improves scores on cognitive tests and memory function.^{41,42} Further research is needed to confirm the mechanism by which hearing aid use affects the rate of cognitive decline in later life.

The strengths of this study lie in its longer-term follow-up, which may have allowed greater time for the accumulation of the benefits of hearing aid use to appear; the longer follow-up period, however, also introduced greater individual differences that may influence cognitive function due to the effects of ageing and disease. In addition, the population-based nature of the HRS sample makes the results of the study generalizable and enhances their external validity. Our findings could thus have substantial public health implications, especially significant the large prevalence of age-related hearing impairment and poor hearing aid uptake among those with hearing impairment. Approximately 33% adults aged 50+ in the US affected by hearing impairment⁴³ and only 40% of those with moderate hearing impairment, used hearing aids.⁴⁴ A report from the National Academies of Sciences, Engineering, and Medicine found that many individuals with hearing impairment do not seek or receive hearing healthcare mainly due to their low awareness of hearing impairment, limited accessibility of the care, and high costs for the hearing technologies. It further recommended a set of actions to improve the accessibility and affordability of hearing healthcare, including strengthen hearing healthcare promotion and provide access of the care for poor population.

⁴⁵ Our findings support the proposition that the timing of beginning hearing aid use is crucial variable for the success of hearing aids as an intervention in old age.⁴⁶ Furthermore, Livingston et al. (2017) categorized hearing impairment as the most prominent midlife risk factor for dementia³ with 55 years being the youngest average age at which the presence of

hearing impairment was shown to be associated with increased risk of dementia.⁴⁷ Preventing hearing loss and/or screening individuals for hearing functioning and providing intervention in the form of hearing aids may preserve cognitive function in older age.

A key limitation in our study is that hearing aid use was identified based on individuals reporting whether they ever wear hearing aids. No information on the frequency of use, the adequacy of amplification or individual's satisfaction with hearing aids was available. Up to 40% of hearing aids dispensed are never or rarely used.⁴⁸ Differing durations and extents of rehabilitative procedures may also lead to different effects on cognitive function. These differences may mask the magnitude of the effect of hearing aid use on cognitive function in this study. As there is high inter-individual variability in hearing aid use, future studies should consider this factor in their models. Another limitation of our study is that the episodic memory tests in the HRS were all presented verbally, and improved hearing may facilitate better performance of those tests. However, our analysis on the visually presented letter cancellation test available in the English Longitudinal Data on Ageing (ELSA) Wave 5 shows that respondents with hearing impairment perform worse than those with no impairment (see Appendix 8).

In sum, we observed a slower decline in episodic memory performance in HRS participants with hearing impairment after beginning to use hearing aids. This association was shown to be independent of risk factors for cognitive impairment and remained significant when we considered attrition in the analysis. Public health efforts to increase access to quality hearing healthcare might delay the onset of cognitive impairment and prove a successful preventive intervention to reduce the impending dementia epidemic.

308 **References**

- 309 1. Prince M., Wimo A, Guerchet M, et al. World Alzheimer Report 2015. The global
310 impact of dementia. An analysis of prevalence, incidence, cost & trends. Alzheimer's Disease
311 International: London. 2015.
- 312 2. Ahmadi-Abhari S, Guzman-Castillo M, Bandosz P, et al. Temporal trend in dementia
313 incidence since 2002 and projections for prevalence in England and Wales to 2040:
314 Modelling study. *BMJ* 2017; 358: p. j2856.
- 315 3. Livingston G, Sommerlad A, Orgeta V, et al. Dementia prevention, intervention, and
316 care. *The Lancet* 2017; 390(10113): 2673-2734.
- 317 4. Maharani A, Piers D, Nazroo J. et al.; on behalf of the Sense-Cog WP1 group,
318 Sensory impairments and cognitive ageing: Evidence from the HRS, ELSA and SHARE. Age
319 and Ageing 2017. Insubmission.
- 320 5. Lin FR. Hearing loss and cognition among older adults in the United States. *Journals*
321 of Gerontology Series A: Biomedical Sciences and Medical Sciences 2011; 66(10): 1131-
322 1136.
- 323 6. Van Boxtel MPJ, Van Beijsterveldt CEM, Jolles PJ, et al. Mild hearing impairment
324 can reduce verbal memory performance in a healthy adult population. *Journal of Clinical and*
325 *Experimental Neuropsychology* 2000; 22(1): 147-154.
- 326 7. Tay T, Wang JJ, Kifley A, et al. Sensory and cognitive association in older persons:
327 findings from an older Australian population. *Gerontology* 2006; 52(6): 386-394.

- 328 8. Lin FR, Yaffe K, Xia J, et al. Hearing loss and cognitive decline in older adults.
329 JAMA Internal Medicine 2013; 173(4): 293-299.
- 330 9. Deal JA, Sharrett AR, Albert MS, et al., Hearing impairment and cognitive decline: a
331 pilot study conducted within the atherosclerosis risk in communities neurocognitive study.
332 American Journal of Epidemiology 2015; 181(9): 680-690.
- 333 10. Valentijn SA, Van Boxtel MPJ, Van Hooren SAH, et al. Change in sensory
334 functioning predicts change in cognitive functioning: Results from a 6-year follow-up in the
335 Maastricht Aging Study. Journal of the American Geriatrics Society 2005; 53(3): 374-380.
- 336 11. Dawes P, Fortnum H, Moore DR, et al. Hearing in middle age: a population snapshot
337 of 40–69 year olds in the UK. Ear and Hearing 2014; 35(3): e44.
- 338 12. Chien W, Lin FR. Prevalence of hearing aid use among older adults in the United
339 States. Archives of Internal Medicine 2012; 172(3): 292-293.
- 340 13. Weinstein BE. Geriatric audiology. 2000: Thieme Medical Publishers.
- 341 14. Lin FR. Hearing loss in older adults: Who's listening? JAMA 2012; 307(11): 1147-
342 1148.
- 343 15. Dawes P, Emsley R, Cruickshanks KJ, et al. Hearing loss and cognition: The role of
344 hearing AIDS, social isolation and depression. PLoS One 2015; 10(3): e0119616.
- 345 16. Lin FR, Ferrucci L, Metter EJ, et al. Hearing loss and cognition in the Baltimore
346 Longitudinal Study of Aging. Neuropsychology 2011; 25(6): 763.

- 347 17. Dawes P, Cruickshanks KJ, Fischer ME, et al. Hearing-aid use and long-term health
348 outcomes: Hearing handicap, mental health, social engagement, cognitive function, physical
349 health, and mortality. *International Journal of Audiology* 2015; 54(11): 838-844.
- 350 18. Kalluri S, Humes LE. Hearing technology and cognition. *American Journal of*
351 *Audiology* 2012; 21(2): 338-343.
- 352 19. Dere E, Easton A, Nadel L, et al. *Handbook of episodic memory*. Vol. 18. 2008:
353 Elsevier.
- 354 20. Bonsang E, Adam S, Perelman S. Does retirement affect cognitive functioning?
355 *Journal of Health Economics* 2012; 31(3): 490-501.
- 356 21. Tampubolon G, Nazroo J, Pendleton N. Trajectories of general cognition and
357 dementia in English older population: An exploration. *European Geriatric Medicine* 2017;
358 8(5-6): 454-459.
- 359 22. Marmot M, Friel S, Bell R, et al. Closing the gap in a generation: Health equity
360 through action on the social determinants of health. *The Lancet* 2008; 372(9650): 1661-1669.
- 361 23. Wilkinson RG, Marmot M. *Social determinants of health: The solid facts*. 2003:
362 World Health Organization.
- 363 24. Tampubolon G. Cognitive ageing in Great Britain in the new century: Cohort
364 differences in episodic memory. *PloS One* 2015; 10(12): e0144907.
- 365 25. Yaffe K. *Chronic medical disease and cognitive aging: Toward a healthy body and*
366 *brain*. 2013: Oxford University Press.

- 367 26. Radloff LS. The CES-D scale: A self-report depression scale for research in the
368 general population. *Applied Psychological Measurement* 1977; 1(3): 385-401.
- 369 27. Chatfield MD, Brayne CE, Matthews FE. A systematic literature review of attrition
370 between waves in longitudinal studies in the elderly shows a consistent pattern of dropout
371 between differing studies. *Journal of Clinical Epidemiology* 2005; 58(1): 13-19.
- 372 28. Matthews FE, Chatfield M, Freeman C, et al., Attrition and bias in the MRC cognitive
373 function and ageing study: an epidemiological investigation. *BMC Public Health* 2004; 4(1):
374 12.
- 375 29. Graham PL, Ryan LM, Luszcz MA. Joint modelling of survival and cognitive decline
376 in the Australian Longitudinal Study of Ageing. *Journal of the Royal Statistical Society:*
377 *Series C (Applied Statistics)* 2011; 60(2): 221-238.
- 378 30. Lindenberger U, Baltes PB. Sensory functioning and intelligence in old age: A strong
379 connection. *Psychology and Aging* 1994; 9(3): 339.
- 380 31. Lindenberger U, Ghisletta P. Cognitive and sensory declines in old age: gauging the
381 evidence for a common cause. *Psychology and Aging* 2009; 24(1): 1.
- 382 32. Wahl HW, Heyl V. Connections between vision, hearing, and cognitive function in
383 old age. *Generations* 2003; 27(1): 39-45.
- 384 33. Birren JE, *The Psychology of Aging*. 1964.
- 385 34. Joore MA, Potjewijd J, Timmerman AA, et al. Response shift in the measurement of
386 quality of life in hearing impaired adults after hearing aid fitting. *Quality of Life Research*
387 2002; 11(4): 299-307.

- 388 35. Mulrow CD, Aguilar C, Endicott JE, et al. Quality-of-life changes and hearing
389 impairment. *Ann Intern Med* 1990; 113(3): 188-94.
- 390 36. Kochkin S, Rogin CM. Quantifying the obvious: The impact of hearing instruments
391 on quality of life. *Hear Rev* 2000; 7(1): 6-34.
- 392 37. Plassman BL, Williams JW, Burke JR, et al. Systematic review: Factors associated
393 with risk for and possible prevention of cognitive decline in later life. *Annals of Internal*
394 *Medicine* 2010; 153(3): 182-193.
- 395 38. Barnes LL, de Leon M, Wilson RS, et al. Social resources and cognitive decline in a
396 population of older African Americans and whites. *Neurology* 2004; 63(12): 2322-2326.
- 397 39. Steffens DC, Otey E, Alexopoulos GS, et al. Perspectives on depression, mild
398 cognitive impairment, and cognitive decline. *Archives of General Psychiatry* 2006; 63(2):
399 130-138.
- 400 40. Bandura A. *Self-efficacy: The exercise of control*. 1997: Macmillan.
- 401 41. Artistic D, Berry JM, Black J, et al. Psychological functioning in adulthood: A self-
402 efficacy analysis. in *Oxford Handbook of Reciprocal Adult Development and Learning*,
403 edited by Carol Hoare, 215-247. 2nd ed. Oxford: Oxford University Press, 2011.
- 404 42. Kim KA, Mueller DJ. Memory, self-efficacy, and adaptability in Korean American
405 older adults: A collective study of four cases. *Educational Gerontology: An International*
406 *Quarterly* 1997; 23(5): 407-423.
- 407 43. Gopinath B, Rochtchina E, Wang JJ, et al. Prevalence of age-related hearing loss in
408 older adults: Blue Mountains Study. *Archives of Internal Medicine* 2009; 169(4): 415-418.

44. Lin FR, Thorpe R, Gordon-Salant S, et al. Hearing loss prevalence and risk factors among older adults in the United States. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 2011; 66(5): 582-590.

45. Blazer D, Liverman C, Domnitz S. *Hearing Health Care: Priorities for Improving Access and Affordability*. National Academies of Sciences, Engineering, and Medicine. 2016. Washington, DC: National Academies Press.

46. Gelfand SA, Silman S, Ross L. Long-term effects of monaural, binaural and no amplification in subjects with bilateral hearing loss. *Scandinavian Audiology* 1987; 16(4): 201-207.

47. Gallacher J, Ilubaera V, Ben-Shlomo Y, et al. Auditory threshold, phonologic demand, and incident dementia. *Neurology* 2012; 79(15): 1583-1590.

48. Vestergaard Knudsen, L., et al., Factors influencing help seeking, hearing aid uptake, hearing aid use and satisfaction with hearing aids: A review of the literature. *Trends in amplification* 2010. 14(3): p. 127-154.

List of tables

Table 1 Characteristics of the HRS sample of hearing aids users (where using hearing aids for the first time between wave 4 and wave 11) at baseline at the first wave observed

	Mean $\pm$ SD (%)	Association with episodic memory scores	
		Coefficient (SE)	<i>P</i> value
Episodic memory scores	10.4 (3.2)	-	-
Age	62.83 (7.73)	-0.08 (0.00)	<0.001
Female	38.04	1.11 (0.14)	<0.001
Education:			
Primary school or less	24.17	reference	
Secondary school	30.2	1.68 (0.19)	<0.001
College or higher	45.64	2.52 (0.17)	<0.001
Married	81.66	0.28 (0.18)	0.128
Smoking behaviour:			
Non-smoker	38.48	reference	
Past smoker	47.35	-0.26 (0.16)	0.101
Current smoker	14.17	-0.38 (0.23)	0.102
Drinking behaviour (units/week)	2.93 (6.14)	0.00 (0.01)	0.583
Doing vigorous physical activity	51.18	0.53 (0.14)	<0.001
Depression score	1.14 (1.72)	-0.24 (0.04)	<0.001
Number of comorbidities	0.87 (0.94)	-0.38 (0.07)	<0.001

Table 2 Hearing aid use and episodic memory scores, coefficients and standard errors.
Source: HRS 1996-2014.

	Model 1		Model 2	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	17.89 (0.36)	<0.001	15.32 (0.4)	<0.001
Age (before using hearing aid)	-0.11 (0.00)	<0.001	-0.1 (0.00)	<0.001
Age (after using hearing aid)	-0.03 (0.00)	<0.001	-0.02 (0.00)	<0.001
Hearing aid use	2.13 (0.41)	<0.001	1.53 (0.41)	<0.001
Female			1.11 (0.09)	<0.001
Married			0.16 (0.07)	0.036
Education , ref: less than high school				
High school			0.97 (0.12)	<0.001
College or higher			1.84 (0.11)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile			0.33 (0.07)	<0.001
3 th tertile (wealthiest)			0.58 (0.08)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker			0.08 (0.09)	0.365
Current smoker			-0.05 (0.13)	0.683
Drinking behaviour			0.01 (0.00)	0.001
Doing vigorous physical activity			0.17 (0.05)	0.001
Depression score			-0.11 (0.01)	<0.001
Number of comorbidities			-0.13 (0.03)	<0.001

444 **List of Figures**

445 **Figure 1** Procedure for the selection of sample (N=1,586) from the HRS core sample waves
446 3-12.

Figure 2 Predicted values of episodic memory before and after beginning to use hearing aids
(time centred at using hearing aids)

Appendix 1 Descriptive statistics of full sample, sample with at least 3 observations and final sample of HRS Waves 3-12.

	Wave 3-12 sample at baseline n=34,506	Wave 3-12 sample with at least 3 observations n=27,984	Final sample n=2,040
Episodic memory scores	10.09 (3.62)	10.33 (3.52)	10.4 (3.2)
Age	62.22 (10.56)	61.29 (9.67)	62.83 (7.73)
Female	56.18	57.04	38.04
Education:			
Primary school or less	30.64	28.95	24.17
Secondary school	28.79	29.22	30.2
College or higher	40.58	41.83	45.64
Married	69.9	71.01	81.66
Smoking behaviour:			
Non-smoker	43.22	43.63	38.48
Past smoker	37.64	37.36	47.35
Current smoker	19.14	19.01	14.17
Drinking behaviour	2.71 (8.94)	2.67 (6.81)	2.93 (6.14)
Doing vigorous physical activity	42.48	44.92	51.18
Depression score	1.49 (1.99)	1.43 (1.95)	1.14 (1.72)
Number of comorbidities	0.93 (1.01)	0.83 (0.94)	0.87 (0.94)

465 **Appendix 2** Hearing aid use and immediate and delayed word recalls, coefficients and
466 standard errors. Source: HRS 1996-2014.
467

	Immediate word recall		Delayed word recall	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	8.18 (0.2)	<0.001	7.15 (0.23)	<0.001
Age (before using hearing aid)	-0.05 (0.00)	<0.001	-0.05 (0.00)	<0.001
Age (after using hearing aid)	-0.00 (0.00)	0.023	-0.01 (0.00)	0.014
Hearing aid use	0.27 (0.21)	0.19	0.87 (0.24)	<0.001
Female	0.51 (0.04)	<0.001	0.57 (0.05)	<0.001
Married	0.06 (0.03)	0.085	0.08 (0.04)	0.080
Education , ref: less than high school				
High school	0.46 (0.05)	<0.001	0.46 (0.07)	<0.001
College or higher	0.88 (0.05)	<0.001	0.92 (0.06)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile	0.16 (0.03)	<0.001	0.14 (0.04)	0.001
3 th tertile (wealthiest)	0.26 (0.04)	<0.001	0.28 (0.05)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker	0.01 (0.04)	0.738	0.07 (0.05)	0.207
Current smoker	-0.05 (0.06)	0.371	-0.00 (0.07)	0.988
Drinking regularly	0.00 (0.00)	0.001	0.00 (0.00)	0.032
Doing vigorous physical activity	0.06 (0.02)	0.015	0.09 (0.03)	0.001
Depression score	-0.04 (0.00)	<0.001	-0.05 (0.00)	<0.001
Number of comorbidities	-0.06 (0.01)	<0.001	-0.05 (0.01)	0.002

468
469

470 **Appendix 3** Predicted values of immediate and delayed memory before and after beginning
471 to use hearing aids (time centred at using hearing aids)

472
473

474 **Appendix 4** Joint model predicting episodic memory scores. Source: HRS 1996-2014

	Coefficient (SE)	P value
Intercept	15.62 (0.26)	<0.001
Age (before using hearing aid)	-0.1 (0.00)	<0.001
Age (after using hearing aid)	-0.02 (0.00)	<0.001
Hearing aid use	0.68 (0.31)	0.031
Female	0.99 (0.04)	<0.001
Married	0.05 (0.06)	0.42
Education , ref: less than high school		
High school	0.84 (0.08)	<0.001
College or higher	1.69 (0.07)	<0.001
Wealth , ref: 1 st tertile (poorest)		
2 nd tertile	0.44 (0.07)	<0.001
3 th tertile (wealthiest)	0.7 (0.07)	<0.001
Smoking behaviour , ref: non-smoker		
Past smoker	-0.01 (0.6)	0.81
Current smoker	-0.06 (0.1)	0.51
Drinking regularly	0.47 (0.09)	0.009
Doing vigorous physical activity	0.18 (0.05)	<0.001
Depression score	-0.14 (0.01)	<0.001
Number of comorbidities	-0.1 (0.02)	<0.001

475

476

477 **Appendix 5** Predicted values of episodic memory using joint model before and after
478 beginning to use hearing aids (time centred at using hearing aids)

479

480

Appendix 6 Hearing aid use and episodic memory scores by gender, coefficients and standard errors. Source: HRS 1996-2014.

	Females (n=768)		Males (n=1,227)	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	17.065 (0.62)	<0.001	14.884 (0.51)	<0.001
Age (before using hearing aid)	-0.118 (0.00)	<0.001	-0.103 (0.00)	<0.001
Age (after using hearing aid)	-0.029 (0.00)	<0.001	-0.027 (0.00)	<0.001
Hearing aid use	1.605 (0.65)	<0.014	1.509 (0.53)	0.004
Married	-0.0008 (0.11)	0.994	0.302 (0.11)	0.007
Education , ref: less than high school				
High school	1.021 (0.21)	<0.001	0.953 (0.15)	<0.001
College or higher	1.722 (0.2)	<0.001	1.934 (0.14)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile	0.444 (0.11)	<0.001	0.254 (0.08)	<0.001
3 th tertile (wealthiest)	0.775 (0.13)	<0.001	0.437 (0.11)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker	0.107 (0.15)	0.497	0.067 (0.12)	0.598
Current smoker	0.086 (0.21)	0.683	-0.132 (0.17)	0.439
Drinking behaviour	0.001 (0.01)	0.924	0.019 (0.00)	<0.001
Doing vigorous physical activity	0.189 (0.08)	0.028	0.165 (0.06)	0.008
Depression score	-0.101 (0.02)	<0.001	-0.132 (0.02)	<0.001
Number of comorbidities	-0.14 (0.05)	0.008	-0.141 (0.03)	<0.001

487 **Appendix 7** Predicted values of episodic memory before and after beginning to use hearing
488 aids (time centred at using hearing aids) by gender

Appendix 8 The comparison of letter cancellation performance between respondents with different sensory function. Source: ELSA Wave 5 (2010).

	N	Mean	Standard deviation
All sample	10,274	18.91	5.4
No hearing impairment	8,121	19.22	5.44
Hearing impairment	2,142	17.66	5.3
p-value*	<0.001		
No visual impairment	8,881	19.16	5.3
Visual impairment	1,381	17.03	5.8
p-value*	<0.001		

Note: *: calculated using chi-square tests.

1 **Title :** Longitudinal relationships between hearing aid use and cognitive function in older
2 Americans

3 **Short running title :** Hearing aid use and cognitive function in older adults

4 **Author :** Asri Maharani, PhD,¹ Piers Dawes, PhD,² James Nazroo, Professor,³ Gindo
5 Tampubolon, PhD,³ and Neil Pendleton, Professor,¹ on behalf of the Sense-Cog WP1
6 group

7 **Corresponding author:** Asri Maharani

8 Address: Humanities Bridgeford Street Building G21, Oxford Road, Manchester M13 9PL,
9 United Kingdom

10 Telephone: +44 161 57025

11 Email address: asri.maharani@manchester.ac.uk

12 **Author affiliation and qualification:**

13 1 Division of Neuroscience and Experimental Psychology, School of Biological Sciences,
14 Faculty of Biology, Medicine and Health, University of Manchester, Manchester Academic
15 Health Science Centre, Manchester M13 9PL, United Kingdom

16 2 Division of Human Communication, Development & Hearing, University of Manchester,
17 Oxford Road, Manchester M13 9PL, United Kingdom

18 3 Sociology and Cathie Marsh Institute for Social Research, University of Manchester
19 Humanities Bridgeford Street Building, Oxford Road, Manchester M13 9PL, United
20 Kingdom

21 **Impact statement:**

22 We certify that this work is novel of recent novel clinical research. This manuscript is
23 important for the literature as it showed for the first time that cognitive decline at different
24 rate before and after the beginning of hearing aid use which holds an important public health
25 implication to improve cognitive health and prevent dementia among older people.

26 **Conflict of interest:**

27 The authors have no financial or any other kind of personal conflicts with this paper.

28 **Authors Contributions:**

29 AM, GT, JN, PD and NP made substantial contributions to the study design. AM analysed
30 the data. GT, JN, PD and NP contributed to the statistical design of the study. AM, GT, JN,
31 PD and NP contributed to the interpretation of the data and wrote each draft of the
32 manuscript. All authors critically reviewed and contributed significantly to the intellectual
33 content of the manuscript. AM had full access to all the data in the study and all authors had
34 final responsibility for the decision to submit for publication.

35 **Acknowledgement:**

36 The Sense-Cog WP1 group are Geir Bertelsen^{1,2}, Suzanne Cosh³, Audrey Cougnard-
37 Grégoire³, Cécile Delcourt³, Fofi Constantinidou⁴, Catherine Helmer³, M. Arfan Ikram^{5,6},
38 Caroline CW Klaver^{5,7}, Iracema Leroi⁸, Magda Meester-Smor^{5,7}, Unal Mutlu^{5,7}, Virginie
39 Nael^{3,9,10}, Henrik Schirmer¹¹, Henning Tiemeier^{5,12}, Therese von Hanno^{13,14}.

40 1: UiT The Arctic University of Norway, Department of Community Medicine, Faculty of
41 Health Sciences, N-9037 Tromsø, Norway

42 2: University Hospital of North Norway, Department of Ophthalmology, N-9038 Tromsø,
43 Norway

3: Univ. Bordeaux, Inserm, Bordeaux Population Health Research Center, team LEHA, UMR 1219, F-33000 Bordeaux, France

4: University of Cyprus, Department of Psychology & Center for Applied Neuroscience, Nicosia, Cyprus

5: Erasmus Medical Centre, Department of Epidemiology, Rotterdam, The Netherlands

6: Erasmus Medical Centre, Departments of Neurology and Radiology, Rotterdam, The Netherlands

7: Erasmus Medical Centre, Department of Ophthalmology, Rotterdam, The Netherlands

8: University of Manchester, Division of Neuroscience and Experimental Psychology, School of Biological Sciences, Manchester, UK

9: Sorbonne University, UMPC University of Paris 06, INSERM, CNRS, Vision Institute, F-75012 Paris, France

10: R&D Life and Vision Science, Essilor International, F-75012 Paris, France

11: UiT-The Arctic University of Norway, Department of Clinical Medicine, Cardiovascular research Group-UNN, N-9037 Tromsø, Norway

12: Erasmus Medical Centre, Department of Psychiatry, Rotterdam, The Netherlands

13: UiT-The Arctic University of Norway, Department of Clinical Medicine, Faculty of Health Sciences, N-9037 Tromsø, Norway

14: Nordland Hospital, Department of Ophthalmology, N-8092 Bodø, Norway

44 **Funding source:**

45 This work was supported by SENSE-Cog project. This project has received funding from the
46 European Union's Horizon 2020 research and innovation programme under grant agreement
47 No 668648.

48 **Abstract word counts:** 195 words

49

|

Main document word counts: 2,~~991~~999 words

50

Number of tables: 2 tables

51

Number of figures: 2 figures

52

For Review Only

53 **Abstract**

54 **Objective:** To test whether hearing aid use alters cognitive trajectories in older adults.

55 **Design, setting, and participants:** Data were drawn from the Health and Retirement Study
56 (HRS), a US population-based longitudinal cohort study with cognitive performance
57 measured repeatedly every 2 years over 18 years (1996-2014). This study included 1,586
58 adults aged 50 and older who took part in a minimum of three waves of the HRS and
59 who used hearing aids for the first time between Wave 4 and Wave 11.

60 **Measurements:** Cognitive outcomes were based on episodic memory scores determined by
61 the sum of immediate and delayed recall of 10 words.

62 **Results:** Hearing aid use was positively associated with episodic memory scores ($\beta=1.24$,
63 $p<0.001$). The decline in episodic memory scores was slower after ($\beta=-0.02$, $p<0.001$) than
64 before using hearing aids ($\beta=-0.1$, $p<0.001$). These results were robust to adjustment for
65 multiple confounders and to attrition as accounted for with joint model.

66 **Conclusions:** Hearing aids may have a mitigating impact on trajectories of cognitive decline
67 in later life. Providing hearing aids or other rehabilitative services for hearing impairment
68 much earlier in the course of hearing impairment may stem the worldwide rise of dementia.

69 Key words: Hearing aid use, cognition, longitudinal analysis

70

71

72

73 **Introduction**

74 Neurodegenerative dementias such as Alzheimer disease are a major health problem in the
75 worldwide aging population. The number of people living with dementia is projected to
76 increase by 57% in the next two decades, from 46 million in 2015 to 72 million in 2050.^{1,2}
77 This rising global prevalence, combined with the lack of effective curative treatment, has
78 rendered the prevention of dementia a public health concern.

79 A recent study by Livingston et al. (2017) showed that intervention on risk factors not
80 including hypertension might prevent 35% of dementia cases³ and that the strongest midlife
81 risk factor for dementia is hearing impairment. It showed that approximately 9% of dementia
82 cases are attributable to hearing loss in midlife. Our previous study, using three longitudinal
83 surveys on ageing health, showed that individuals with hearing and visual impairments had
84 lower episodic memory scores and a more adverse trajectory of decline in memory scores
85 with age than those with no impairment.⁴ The relationship between of hearing impairment
86 and lower cognitive ability in later life has also been reported by numerous cross-sectional⁵⁻⁷
87 and longitudinal studies.⁸⁻¹⁰ As ~~sensory-hearing~~ impairment is prevalent, alleviating it ~~partly~~
88 might ~~have a great impact on when elderly~~~~delay the point that older adults~~ cross the critical
89 ~~line-threshold of impairment~~ into dementia.

90 Hearing impairment as a risk factor for dementia is not only greater than other individual
91 midlife risks but is also relevant to many individuals because of its relatively high prevalence
92 in middle and old age. At least 10% of individuals aged 40 to 69 years show some degree of
93 measurable hearing impairment¹¹ and that this proportion increases with age. The prevalence
94 of hearing impairment increases to 30% of individuals over the age of 65, and between 70%
95 and 90% individuals over the age of 85 experience some hearing loss.^{12,13} Although hearing
96 impairment is highly prevalent, it remains largely under treated.¹⁴ Only 1 in 7 adults aged 50+

97 with hearing impairment use hearing aids, and this figure declines to fewer than 1 in 20 for
98 working-aged adults (50-59 years old).¹²

99 The effect of hearing aid interventions on cognitive function remains poorly understood.
100 Cross-sectional studies from the US⁵ and the UK¹⁵ have reported that hearing aid use is
101 associated with better cognitive scores. In contrast, a study using a cross-sectional cohort of
102 the Baltimore Longitudinal Study of Aging found no significant relationship between hearing
103 aid use and cognitive ability.¹⁶ The insignificant effect of hearing aid use on cognitive
104 function was also shown in several small longitudinal studies of short duration.^{8-10,17,18}

105 We used an 18-year follow-up of the Health and Retirement Study cohort to assess the
106 consequences of hearing aid use on long-term age-related decline in episodic memory. Using
107 a self-reported measure of hearing aid use, the association between hearing impairment and
108 cognitive trajectories over 18 years was investigated in a community-based cohort of older
109 adults, and the trajectories of the individuals before using hearing aids were compared with
110 those after beginning to use hearing aids.

111 **Methods**

112 This study forms part of the SENSE-Cog multi-phase research programme, funded by the
113 European Union Horizon 2020 programme. SENSE-Cog aims to promote mental well-being
114 in older adults with sensory and cognitive impairments (<http://www.sense-cog.eu/>). The first
115 work package of this project aims to better understand the links among sensory, cognitive and
116 mental ill-health in older Europeans.

117

118

Study population

Our empirical analysis used the Health and Retirement Study (HRS) Waves 3 (1996-97) – 12 (2014-15). The HRS is an ongoing biennial investigation of US adults aged 50 years and older that started in 1992. ~~The respondents of the first wave were community dwelling Americans born between 1931 and 1941 and their partners. Since the fourth wave (1998), this survey has also included participants from the Asset and Health Dynamics Among the Oldest Old (AHEAD) study as well as a representative sample of individuals born between 1924 and 1947.~~ Sponsored by the National Institute of Aging and performed by the Institute for Social Research at the University of Michigan, the HRS provides information on demographic, socio-economic factors, and health.

We used Wave 3 and later of the HRS as the episodic memory scores using 10 words were first available in the third wave. In our study, we restricted the sample to respondents age 50 years and older who responded to at least three waves of HRS, had no dementia in the baseline, and used hearing aids for the first time between Waves 4 and 11. This gave a sample of 2,040 individuals with the selection procedure as illustrated in Figure 1. We describe the characteristics of the HRS core sample Waves 3-12, HRS core sample with at least 3 observations and the final sample in Appendix 1. It shows that the average of age and episodic memory scores of the core sample Waves 3-12 and final sample are similar.

Measures

The measures of cognitive ability in the HRS are the outcomes of simple tests, e.g. immediate and delayed word recall (episodic memory), serial 7's test, backwards count starting from 20, and date naming. In our analysis, we focused on one specific cognitive domain available in all HRS waves used in this study: episodic memory. We were particularly interested in

episodic memory scores as they are more age-sensitive than other cognitive measures,¹⁹ do not suffer from floor or ceiling effects,²⁰ have a common mechanism with cognitive control variables¹⁴ and have a strong association with dementia. After allowing for established risk factors for dementia, the odds ratio for dementia among members of the most advantaged trajectory of episodic memory was more than five times lower than the reference (disadvantaged) trajectory.²¹ In the HRS memory test, the interviewer read a list of 10 simple nouns (e.g. book, child, hotel, etc.) once and the participants were asked to repeat those nouns on two occasions: immediately after the words were read out (immediate recall) and after a short interval (delayed recall). ~~Following Bonsang et al. (2012),²⁰ we~~ We calculated the episodic memory score as the sum of the number of target words recalled at the immediate and the delayed recall phase (score ranging from 0 to 20).²⁰

The timing of using hearing aids for the first time was based on self-definition through the question: ‘Do you ever wear a hearing aid?’. This question was posed to all respondents. Based on the first time that respondents answered ‘yes’ to that question, we constructed a dummy variable for hearing aid use (1 for the wave the first time the respondents used hearing aids and after, 0 for the wave before the respondents used hearing aids). In total, 1,586 respondents used hearing aids for the first time during the fourteen-year period.

We included an extensive set of covariates as identified as risk factors for cognitive decline in prior studies.²²⁻²⁵ Demographic covariates included age (in years) and sex (female as the reference). Socio-economic covariates included education (less than high school, high school, and college or higher), marital status (married or cohabiting, and not married) and wealth (tertiles of income each wave). ~~Respondents’ educational attainments were categorised as less than high school (as the reference), high school, and college or higher. Marital status was categorised as married or cohabiting, and not married (as the reference). For wealth, we used~~

~~tertiles of income each year, using the poorest tertile as the reference.~~ The lifestyle behaviour covariates included smoking, drinking behaviour and physical activities. For smoking behaviour, respondents were classified as non-smokers, past smokers and current smokers. We used the number of units per week to measure drinking behaviour. Depressive symptoms were assessed with the 8-item Centre for Epidemiological Studies Depression Scale.²⁶ Lastly, the number of comorbidities present was included as the sum of several chronic diseases: heart disease, high blood pressure, lung diseases, diabetes, stroke and cancer.

Statistical analysis

To model trajectories in episodic memory scores, we used hierarchical linear regression analysis, which is designed to analyse longitudinal data. In this regression analysis, intra-individual correlation is modelled using an individual specific random intercept and an individual specific random slope. This analysis thus takes into account multiple observations within individual and intra-individual correlation. In addition, it allows for adjustment of potential confounding variables. We used a spline model with a knot at the beginning of hearing aid use and assessed whether the slope before using hearing aid differed to the post-hearing aid use slope. We included the hearing aid variable (coded as 1 after using hearing aids and 0 prior to using hearing aids) and its interaction with the slope term (age) to test the differences in cognitive trajectories before and after beginning to use hearing aids. The associations between hearing aid use, age, age interaction with hearing aid use and episodic memory scores were quantified in the first model. The demographic and socio-economic determinants (age, gender, education, marital status, and wealth) and the variables representing lifestyle behaviour, depression, and the number of chronic diseases present were added in the final model.

190 *Sensitivity analysis*

191 For the first sensitivity analysis, we conducted two separated hierarchical linear regression
192 analyses with immediate and delayed word recall as the outcomes, while the second analysis
193 focused on attrition. The HRS, like other longitudinal studies on ageing is subject to attrition
194 in which respondents ~~who drop out are not a random sample. Respondents~~ are prone to
195 selective dropout due to death or poor health.^{27,28} Ignoring those dropouts thus can result in
196 bias in the analysis. We tested the sensitivity of our results to attrition by using a joint
197 model.²⁹ This resultant division into two parts, the growth curve model and the survival
198 model, allowed the random effects to influence both episodic memory and attrition. Finally,
199 we examined the role of gender in the association between hearing aid use and cognitive
200 function by conducting separate analyses for females and males. The models were
201 constructed using STATA 14 and Latent Gold 5.1.

202 **Results**

203 Table 1 shows the descriptive statistics of 2,040 HRS sample respondents who used hearing
204 aids for the first time between Waves 4 and 11 at the first wave observed. The episodic
205 memory score has a distribution close to the normal distribution with a sample mean of 10.4
206 and a standard deviation of 3.2. On average the respondents used hearing aids for the first
207 time at 63 years old. The respondents were mostly males (61%) who had completed college
208 or higher (45%) and were married (81%). The bivariate regression model (see Table 1,
209 second and third columns) shows that age, depression score, and number of comorbidities
210 have a negative and significant association with episodic memory scores. Being relatively
211 well educated, drinking alcohol and engaging regularly in physical activities are positively
212 associated with episodic memory scores.

213 The parameter estimates for the slope of episodic memory scores before and after beginning
214 to use hearing aids in an initial model are presented in Table 2, left pane. Episodic memory
215 declined significantly with the addition of age, but the rate of the decline was slower after
216 beginning to use hearing aids ($\beta=-0.03$, $p<0.001$) than before ($\beta=-0.11$, $p<0.001$). The
217 difference of the coefficient between those two slopes is 0.08 ($p<0.001$). In this model,
218 hearing aid use was associated with higher memory scores ($\beta=2.13$, $p<0.001$). The
219 association between hearing aid use and episodic memory scores remained significant when
220 we included the risk factors in the second model ($\beta=1.24$, $p<0.001$). In this second model,
221 slopes for the decline of episodic memory scores remained steeper before beginning hearing
222 aid use ($\beta=-0.1$, $p<0.001$) than after ($\beta=-0.02$, $p<0.001$).

223 In the second model, several potential confounders and socio-demographic characteristics
224 showed significant associations with episodic memory scores. Being female, having attained
225 a higher level of education, having a higher income, drinking alcohol and engaging in regular
226 physical exercise were positively associated with episodic memory scores. Depression scores
227 and the presence of chronic diseases were associated with lower memory scores.

228 Figure 2 illustrates the change in episodic memory scores over time. The graph is centred at
229 the first time an individual used hearing aids. It is centred on the point of time at which as
230 individual used hearing aids for the first time. The lines to the left of the centre of the graph
231 shows the rate of change in episodic memory score in the years leading up to beginning
232 hearing aid use, and the lines to the right of the centre of the graph shows the rate of change
233 in episodic memory following the beginning of hearing aid use. The model is adjusted for
234 demographic, socio-economic, lifestyle behaviour and health status. For all individuals, there
235 is a decline in episodic memory leading up to hearing aid use. The episodic memory scores

continue to decline after beginning to use hearing aids; however, the rate of decline is less steep.

The first sensitivity analysis shows that both the immediate and delayed word recall scores declined significantly before using hearing aids ($\beta = 0.05, p < 0.001$) and this significant decline diminished after beginning to use hearing aids (see Appendix 2 and 3) ($\beta = 0.00, p = 0.023$). ~~Similarly, the delayed recall scores decline was gentler after ($\beta = 0.05, p < 0.001$) than before the beginning of hearing aid use ($\beta = 0.01, p = 0.014$). This sensitivity analysis shows that our findings are robust.~~ For the second sensitivity analysis (see Appendix 34 and 5), we found that the slope of cognitive decline before and after beginning to use hearing aids in the joint model is similar to that in the growth curve model. These findings indicate that our findings are robust. Our final sensitivity analysis showed that although females performed better than males in the episodic memory test, they have similar rate of cognitive decline before and after using hearing aids for the first time (see Appendix 6 and 7).

Discussion

Using a national representative survey spanning 18 years, our study shows a less steep decrease in episodic memory performance after beginning to use hearing aids compared to before using hearing aids. The reduced rate of decline following hearing aid use remained significant after we took attrition into account. From the theoretical point of view, this finding provides new evidence to disentangle the relationship between cognitive function and hearing impairment. In prior studies, two main hypotheses have been posited to explain this relationship. The ‘common cause hypothesis’ argues that hearing impairment and cognitive decline share common age-related change factors such as the degeneration of the central nervous system.^{30,31} The ‘cascade hypothesis’, on the other hand, claims that prolonged reduction of hearing function leads to insufficient stimulation, which may in turn cause

260 cognitive decline in later life.^{8,15,32,33} These hypotheses lead to different predictions regarding
261 on the impact of hearing aid use on cognition. According to the common cause hypotheses,
262 hearing aids may not affect cognition given that degeneration of central nervous system
263 affects regardless of the maintenance of good hearing function.

264 The slower rate of cognitive decline among those with hearing impairment who have begun
265 hearing aid use thus supports the cascade hypothesis. According to this hypothesis, hearing
266 aids may allow better hearing input and delay cognitive decline through either preventing the
267 adverse effects of auditory deprivation or facilitating lower levels of depression symptoms,
268 increased social engagement, and higher self-efficacy that have a positive impact on
269 cognitive function. Prior studies have reported that hearing aid users experienced less anxiety
270 and depression^{34,35} and better quality of social engagement after beginning to use hearing
271 aids; both lower social engagement and depression are independently associated with
272 cognitive decline.³⁷⁻³⁹ Another mechanism through which hearing aids may reduce the rate
273 of cognitive decline is that they may enhance self-efficacy, the belief in one's own ability to
274 accomplish tasks or succeed in specific situations,⁴⁰ which in turn improves scores on
275 cognitive tests and memory function.^{41,42} Further research is needed to confirm the
276 mechanism by which hearing aid use affects the rate of cognitive decline in later life.

277 The strengths of this study lie in its longer-term follow-up, which may have allowed greater
278 time for the accumulation of the benefits of hearing aid use to appear; the longer follow-up
279 period, however, also introduced greater individual differences that may influence cognitive
280 function due to the effects of ageing and disease. In addition, the population-based nature of
281 the HRS sample makes the results of the study generalizable and enhances their external
282 validity. Our findings could thus have substantial public health implications, especially
283 significant the large prevalence of age-related hearing impairment and poor hearing aid

uptake among those with hearing impairment. Approximately 33% adults aged 50+ in the US affected by hearing impairment⁴³ and only 40% of those with moderate hearing impairment, used hearing aids.⁴⁴ A report from the National Academies of Sciences, Engineering, and Medicine found that many individuals with hearing impairment do not seek or receive hearing healthcare mainly due to their low awareness of hearing impairment, limited accessibility of the care, and high costs for the hearing technologies. It further recommended a set of actions to improve the accessibility and affordability of hearing healthcare, including strengthen hearing healthcare promotion and provide access of the care for poor population.⁴⁵ Our findings support the proposition that the timing of beginning hearing aid use is crucial variable for the success of hearing aids as an intervention in old age.⁴⁵⁻⁴⁶ Furthermore, Livingston et al. (2017) categorized hearing impairment as the most prominent midlife risk factor for dementia³ with 55 years being the youngest average age at which the presence of hearing impairment was shown to be associated with increased risk of dementia.⁴⁶⁻⁴⁷ Preventing hearing loss and/or screening individuals for hearing functioning and providing intervention in the form of hearing aids may preserve cognitive function in older age.

A key limitation in our study is that hearing aid use was identified based on individuals reporting whether they ever wear hearing aids. No information on the frequency of use, the adequacy of amplification or individual's satisfaction with hearing aids was available. Up to 40% of hearing aids dispensed are never or rarely used.⁴⁷⁻⁴⁸ Differing durations and extents of rehabilitative procedures may also lead to different effects on cognitive function. These differences may mask the magnitude of the effect of hearing aid use on cognitive function in this study. As there is high inter-individual variability in hearing aid use, future studies should consider this factor in their models. Another limitation of our study is that the episodic memory tests in the HRS were all presented verbally, and improved hearing may facilitate better performance of those tests. However, our analysis on the visually presented letter

cancellation test available in the English Longitudinal Data on Ageing (ELSA) Wave 5 shows that respondents with hearing impairment perform worse than those with no impairment (see Appendix [48](#)).

In sum, we observed a slower decline in episodic memory performance in HRS participants with hearing impairment after beginning to use hearing aids. This association was shown to be independent of risk factors for cognitive impairment and remained significant when we considered attrition in the analysis. Public health efforts to increase access to quality hearing healthcare might delay the onset of cognitive impairment and prove a successful preventive intervention to reduce the impending dementia epidemic.

319 **References**

- 320 1. Prince M., Wimo A, Guerchet M, et al. World Alzheimer Report 2015. The global
321 impact of dementia. An analysis of prevalence, incidence, cost & trends. Alzheimer's Disease
322 International: London. 2015.
- 323 2. Ahmadi-Abhari S, Guzman-Castillo M, Bandosz P, et al. Temporal trend in dementia
324 incidence since 2002 and projections for prevalence in England and Wales to 2040:
325 Modelling study. BMJ 2017; 358: p. j2856.
- 326 3. Livingston G, Sommerlad A, Orgeta V, et al. Dementia prevention, intervention, and
327 care. The Lancet 2017; 390(10113): 2673-2734.
- 328 4. Maharani A, Piers D, Nazroo J. et al.; on behalf of the Sense-Cog WP1 group,
329 Sensory impairments and cognitive ageing: Evidence from the HRS, ELSA and SHARE. Age
330 and Ageing 2017. Insubmission.
- 331 5. Lin FR. Hearing loss and cognition among older adults in the United States. Journals
332 of Gerontology Series A: Biomedical Sciences and Medical Sciences 2011; 66(10): 1131-
333 1136.
- 334 6. Van Boxtel MPJ, Van Beijsterveldt CEM, Jolles PJ, et al. Mild hearing impairment
335 can reduce verbal memory performance in a healthy adult population. Journal of Clinical and
336 Experimental Neuropsychology 2000; 22(1): 147-154.
- 337 7. Tay T, Wang JJ, Kifley A, et al. Sensory and cognitive association in older persons:
338 findings from an older Australian population. Gerontology 2006; 52(6): 386-394.

- 339 8. Lin FR, Yaffe K, Xia J, et al. Hearing loss and cognitive decline in older adults.
340 JAMA Internal Medicine 2013; 173(4): 293-299.
- 341 9. Deal JA, Sharrett AR, Albert MS, et al., Hearing impairment and cognitive decline: a
342 pilot study conducted within the atherosclerosis risk in communities neurocognitive study.
343 American Journal of Epidemiology 2015; 181(9): 680-690.
- 344 10. Valentijn SA, Van Boxtel MPJ, Van Hooren SAH, et al. Change in sensory
345 functioning predicts change in cognitive functioning: Results from a 6-year follow-up in the
346 Maastricht Aging Study. Journal of the American Geriatrics Society 2005; 53(3): 374-380.
- 347 11. Dawes P, Fortnum H, Moore DR, et al. Hearing in middle age: a population snapshot
348 of 40–69 year olds in the UK. Ear and Hearing 2014; 35(3): e44.
- 349 12. Chien W, Lin FR. Prevalence of hearing aid use among older adults in the United
350 States. Archives of Internal Medicine 2012; 172(3): 292-293.
- 351 13. Weinstein BE. Geriatric audiology. 2000: Thieme Medical Publishers.
- 352 14. Lin FR. Hearing loss in older adults: Who's listening? JAMA 2012; 307(11): 1147-
353 1148.
- 354 15. Dawes P, Emsley R, Cruickshanks KJ, et al. Hearing loss and cognition: The role of
355 hearing AIDS, social isolation and depression. PLoS One 2015; 10(3): e0119616.
- 356 16. Lin FR, Ferrucci L, Metter EJ, et al. Hearing loss and cognition in the Baltimore
357 Longitudinal Study of Aging. Neuropsychology 2011; 25(6): 763.

- 358 17. Dawes P, Cruickshanks KJ, Fischer ME, et al. Hearing-aid use and long-term health
359 outcomes: Hearing handicap, mental health, social engagement, cognitive function, physical
360 health, and mortality. *International Journal of Audiology* 2015; 54(11): 838-844.
- 361 18. Kalluri S, Humes LE. Hearing technology and cognition. *American Journal of*
362 *Audiology* 2012; 21(2): 338-343.
- 363 19. Dere E, Easton A, Nadel L, et al. *Handbook of episodic memory*. Vol. 18. 2008:
364 Elsevier.
- 365 20. Bonsang E, Adam S, Perelman S. Does retirement affect cognitive functioning?
366 *Journal of Health Economics* 2012; 31(3): 490-501.
- 367 21. Tampubolon G, Nazroo J, Pendleton N. Trajectories of general cognition and
368 dementia in English older population: An exploration. *European Geriatric Medicine* 2017;
369 8(5-6): 454-459.
- 370 22. Marmot M, Friel S, Bell R, et al. Closing the gap in a generation: Health equity
371 through action on the social determinants of health. *The Lancet* 2008; 372(9650): 1661-1669.
- 372 23. Wilkinson RG, Marmot M. *Social determinants of health: The solid facts*. 2003:
373 World Health Organization.
- 374 24. Tampubolon G. Cognitive ageing in Great Britain in the new century: Cohort
375 differences in episodic memory. *PloS One* 2015; 10(12): e0144907.
- 376 25. Yaffe K. *Chronic medical disease and cognitive aging: Toward a healthy body and*
377 *brain*. 2013: Oxford University Press.

- 378 26. Radloff LS. The CES-D scale: A self-report depression scale for research in the
379 general population. *Applied Psychological Measurement* 1977; 1(3): 385-401.
- 380 27. Chatfield MD, Brayne CE, Matthews FE. A systematic literature review of attrition
381 between waves in longitudinal studies in the elderly shows a consistent pattern of dropout
382 between differing studies. *Journal of Clinical Epidemiology* 2005; 58(1): 13-19.
- 383 28. Matthews FE, Chatfield M, Freeman C, et al., Attrition and bias in the MRC cognitive
384 function and ageing study: an epidemiological investigation. *BMC Public Health* 2004; 4(1):
385 12.
- 386 29. Graham PL, Ryan LM, Luszcz MA. Joint modelling of survival and cognitive decline
387 in the Australian Longitudinal Study of Ageing. *Journal of the Royal Statistical Society:*
388 *Series C (Applied Statistics)* 2011; 60(2): 221-238.
- 389 30. Lindenberger U, Baltes PB. Sensory functioning and intelligence in old age: A strong
390 connection. *Psychology and Aging* 1994; 9(3): 339.
- 391 31. Lindenberger U, Ghisletta P. Cognitive and sensory declines in old age: gauging the
392 evidence for a common cause. *Psychology and Aging* 2009; 24(1): 1.
- 393 32. Wahl HW, Heyl V. Connections between vision, hearing, and cognitive function in
394 old age. *Generations* 2003; 27(1): 39-45.
- 395 33. Birren JE, *The Psychology of Aging*. 1964.
- 396 34. Joore MA, Potjewijd J, Timmerman AA, et al. Response shift in the measurement of
397 quality of life in hearing impaired adults after hearing aid fitting. *Quality of Life Research*
398 2002; 11(4): 299-307.

- 399 35. Mulrow CD, Aguilar C, Endicott JE, et al. Quality-of-life changes and hearing
400 impairment. *Ann Intern Med* 1990; 113(3): 188-94.
- 401 36. Kochkin S, Rogin CM. Quantifying the obvious: The impact of hearing instruments
402 on quality of life. *Hear Rev* 2000; 7(1): 6-34.
- 403 37. Plassman BL, Williams JW, Burke JR, et al. Systematic review: Factors associated
404 with risk for and possible prevention of cognitive decline in later life. *Annals of Internal*
405 *Medicine* 2010; 153(3): 182-193.
- 406 38. Barnes LL, de Leon M, Wilson RS, et al. Social resources and cognitive decline in a
407 population of older African Americans and whites. *Neurology* 2004; 63(12): 2322-2326.
- 408 39. Steffens DC, Otey E, Alexopoulos GS, et al. Perspectives on depression, mild
409 cognitive impairment, and cognitive decline. *Archives of General Psychiatry* 2006; 63(2):
410 130-138.
- 411 40. Bandura A. *Self-efficacy: The exercise of control*. 1997: Macmillan.
- 412 41. Artistic D, Berry JM, Black J, et al. Psychological functioning in adulthood: A self-
413 efficacy analysis. in *Oxford Handbook of Reciprocal Adult Development and Learning*,
414 edited by Carol Hoare, 215-247. 2nd ed. Oxford: Oxford University Press, 2011.
- 415 42. Kim KA, Mueller DJ. Memory, self-efficacy, and adaptability in Korean American
416 older adults: A collective study of four cases. *Educational Gerontology: An International*
417 *Quarterly* 1997; 23(5): 407-423.
- 418 43. Gopinath B, Rochtchina E, Wang JJ, et al. Prevalence of age-related hearing loss in
419 older adults: Blue Mountains Study. *Archives of Internal Medicine* 2009; 169(4): 415-418.

44. Lin FR, Thorpe R, Gordon-Salant S, et al. Hearing loss prevalence and risk factors among older adults in the United States. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences* 2011; 66(5): 582-590.

45. Blazer D, Liverman C, Domnitz S. Hearing Health Care: Priorities for Improving Access and Affordability. National Academies of Sciences, Engineering, and Medicine. 2016. Washington, DC: National Academies Press.

~~45~~46. Gelfand SA, Silman S, Ross L. Long-term effects of monaural, binaural and no amplification in subjects with bilateral hearing loss. *Scandinavian Audiology* 1987; 16(4): 201-207.

~~46~~47. Gallacher J, Ilubaera V, Ben-Shlomo Y, et al. Auditory threshold, phonologic demand, and incident dementia. *Neurology* 2012; 79(15): 1583-1590.

~~47~~48. Vestergaard Knudsen, L., et al., Factors influencing help seeking, hearing aid uptake, hearing aid use and satisfaction with hearing aids: A review of the literature. *Trends in amplification* 2010. 14(3): p. 127-154.

List of tables

Table 1 Characteristics of the HRS sample of hearing aids users (where using hearing aids for the first time between wave 4 and wave 11) at baseline at the first wave observed

	Mean $\pm$ SD (%)	Association with episodic memory scores	
		Coefficient (SE)	P value
Episodic memory scores	10.4 (3.2)	-	-
Age	62.83 (7.73)	-0.08 (0.00)	<0.001
Female	38.04	1.11 (0.14)	<0.001
Education:			
Primary school or less	24.17	reference	
Secondary school	30.2	1.68 (0.19)	<0.001
College or higher	45.64	2.52 (0.17)	<0.001
Married	81.66	0.28 (0.18)	0.128
Smoking behaviour:			
Non-smoker	38.48	reference	
Past smoker	47.35	-0.26 (0.16)	0.101
Current smoker	14.17	-0.38 (0.23)	0.102
Drinking behaviour (units/week)	2.93 (6.14)	0.00 (0.01)	0.583
Doing vigorous physical activity	51.18	0.53 (0.14)	<0.001
Depression score	1.14 (1.72)	-0.24 (0.04)	<0.001
Number of comorbidities	0.87 (0.94)	-0.38 (0.07)	<0.001

Table 2 Hearing aid use and episodic memory scores, coefficients and standard errors.
Source: HRS 1996-2014.

	Model 1		Model 2	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	17.89 (0.36)	<0.001	15.32 (0.4)	<0.001
Age (before using hearing aid)	-0.11 (0.00)	<0.001	-0.1 (0.00)	<0.001
Age (after using hearing aid)	-0.03 (0.00)	<0.001	-0.02 (0.00)	<0.001
Hearing aid use	2.13 (0.41)	<0.001	1.53 (0.41)	<0.001
Female			1.11 (0.09)	<0.001
Married			0.16 (0.07)	0.036
Education , ref: less than high school				
High school			0.97 (0.12)	<0.001
College or higher			1.84 (0.11)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile			0.33 (0.07)	<0.001
3 th tertile (wealthiest)			0.58 (0.08)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker			0.08 (0.09)	0.365
Current smoker			-0.05 (0.13)	0.683
Drinking behaviour			0.01 (0.00)	0.001
Doing vigorous physical activity			0.17 (0.05)	0.001
Depression score			-0.11 (0.01)	<0.001
Number of comorbidities			-0.13 (0.03)	<0.001

Predicted values of episodic memory before and after beginning to use hearing aids (time centred at using hearing aids)

99x72mm (300 x 300 DPI)

Appendix 1 Descriptive statistics of full sample, sample with at least 3 observations and final sample of HRS Waves 3-12.

	Wave 3-12 sample at baseline n=34,506	Wave 3-12 sample with at least 3 observations n=27,984	Final sample n=2,040
Episodic memory scores	10.09 (3.62)	10.33 (3.52)	10.4 (3.2)
Age	62.22 (10.56)	61.29 (9.67)	62.83 (7.73)
Female	56.18	57.04	38.04
Education:			
Primary school or less	30.64	28.95	24.17
Secondary school	28.79	29.22	30.2
College or higher	40.58	41.83	45.64
Married	69.9	71.01	81.66
Smoking behaviour:			
Non-smoker	43.22	43.63	38.48
Past smoker	37.64	37.36	47.35
Current smoker	19.14	19.01	14.17
Drinking behaviour	2.71 (8.94)	2.67 (6.81)	2.93 (6.14)
Doing vigorous physical activity	42.48	44.92	51.18
Depression score	1.49 (1.99)	1.43 (1.95)	1.14 (1.72)
Number of comorbidities	0.93 (1.01)	0.83 (0.94)	0.87 (0.94)

Appendix 2 Hearing aid use and immediate and delayed word recalls, coefficients and standard errors. Source: HRS 1996-2014.

	Immediate word recall		Delayed word recall	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	8.18 (0.2)	<0.001	7.15 (0.23)	<0.001
Age (before using hearing aid)	-0.05 (0.00)	<0.001	-0.05 (0.00)	<0.001
Age (after using hearing aid)	-0.00 (0.00)	0.023	-0.01 (0.00)	0.014
Hearing aid use	0.27 (0.21)	0.19	0.87 (0.24)	<0.001
Female	0.51 (0.04)	<0.001	0.57 (0.05)	<0.001
Married	0.06 (0.03)	0.085	0.08 (0.04)	0.080
Education , ref: less than high school				
High school	0.46 (0.05)	<0.001	0.46 (0.07)	<0.001
College or higher	0.88 (0.05)	<0.001	0.92 (0.06)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile	0.16 (0.03)	<0.001	0.14 (0.04)	0.001
3 th tertile (wealthiest)	0.26 (0.04)	<0.001	0.28 (0.05)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker	0.01 (0.04)	0.738	0.07 (0.05)	0.207
Current smoker	-0.05 (0.06)	0.371	-0.00 (0.07)	0.988
Drinking regularly	0.00 (0.00)	0.001	0.00 (0.00)	0.032
Doing vigorous physical activity	0.06 (0.02)	0.015	0.09 (0.03)	0.001
Depression score	-0.04 (0.00)	<0.001	-0.05 (0.00)	<0.001
Number of comorbidities	-0.06 (0.01)	<0.001	-0.05 (0.01)	0.002

Appendix 4 Joint model predicting episodic memory scores. Source: HRS 1996-2014

	Coefficient (SE)	P value
Intercept	15.62 (0.26)	<0.001
Age (before using hearing aid)	-0.1 (0.00)	<0.001
Age (after using hearing aid)	-0.02 (0.00)	<0.001
Hearing aid use	0.68 (0.31)	0.031
Female	0.99 (0.04)	<0.001
Married	0.05 (0.06)	0.42
Education , ref: less than high school		
High school	0.84 (0.08)	<0.001
College or higher	1.69 (0.07)	<0.001
Wealth , ref: 1 st tertile (poorest)		
2 nd tertile	0.44 (0.07)	<0.001
3 th tertile (wealthiest)	0.7 (0.07)	<0.001
Smoking behaviour , ref: non-smoker		
Past smoker	-0.01 (0.6)	0.81
Current smoker	-0.06 (0.1)	0.51
Drinking regularly	0.47 (0.09)	0.009
Doing vigorous physical activity	0.18 (0.05)	<0.001
Depression score	-0.14 (0.01)	<0.001
Number of comorbidities	-0.1 (0.02)	<0.001

Appendix 6 Hearing aid use and episodic memory scores by gender, coefficients and standard errors. Source: HRS 1996-2014.

	Females (n=768)		Males (n=1,227)	
	Coefficient (SE)	P value	Coefficient (SE)	P value
Intercept	17.065 (0.62)	<0.001	14.884 (0.51)	<0.001
Age (before using hearing aid)	-0.118 (0.00)	<0.001	-0.103 (0.00)	<0.001
Age (after using hearing aid)	-0.029 (0.00)	<0.001	-0.027 (0.00)	<0.001
Hearing aid use	1.605 (0.65)	<0.014	1.509 (0.53)	0.004
Married	-0.0008 (0.11)	0.994	0.302 (0.11)	0.007
Education , ref: less than high school				
High school	1.021 (0.21)	<0.001	0.953 (0.15)	<0.001
College or higher	1.722 (0.2)	<0.001	1.934 (0.14)	<0.001
Wealth , ref: 1 st tertile (poorest)				
2 nd tertile	0.444 (0.11)	<0.001	0.254 (0.08)	<0.001
3 th tertile (wealthiest)	0.775 (0.13)	<0.001	0.437 (0.11)	<0.001
Smoking behaviour , ref: non-smoker				
Past smoker	0.107 (0.15)	0.497	0.067 (0.12)	0.598
Current smoker	0.086 (0.21)	0.683	-0.132 (0.17)	0.439
Drinking behaviour	0.001 (0.01)	0.924	0.019 (0.00)	<0.001
Doing vigorous physical activity	0.189 (0.08)	0.028	0.165 (0.06)	0.008
Depression score	-0.101 (0.02)	<0.001	-0.132 (0.02)	<0.001
Number of comorbidities	-0.14 (0.05)	0.008	-0.141 (0.03)	<0.001

Appendix 8 The comparison of letter cancellation performance between respondents with different sensory function. Source: ELSA Wave 5 (2010).

	N	Mean	Standard deviation
All sample	10,274	18.91	5.4
No hearing impairment	8,121	19.22	5.44
Hearing impairment	2,142	17.66	5.3
p-value*	<0.001		
No visual impairment	8,881	19.16	5.3
Visual impairment	1,381	17.03	5.8
p-value*	<0.001		

Note: *: calculated using chi-square tests.

276x201mm (72 x 72 DPI)

453x329mm (72 x 72 DPI)

276x201mm (72 x 72 DPI)