The effect of functional hearing and hearing aid usage on verbal reasoning in a large community-dwelling population

Gitte Keidser[a], Mary Rudner[b], Mark Seeto[a], Staffan Hygge[c], Jerker Ronnberg[b]

[a]National Acoustic Laboratories, Sydney, Australia

[b]Linnaeus Centre HEAD, Swedish Institute for Disability Research, Department of Behavioural Sciences and Learning, Linköping University, Sweden

[c]Environmental Psychology, Faculty of Engineering and Sustainable Development, University of Gävle, Sweden

Address for correspondence:

Gitte Keidser, National Acoustic Laboratories, Australian Hearing Hub, 16 University Avenue, Macquarie University, NSW 2109, Australia

Email: gitte.keidser@nal.gov.au

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Abstract

Objectives: Verbal reasoning performance is an indicator of the ability to think constructively in everyday life, and relies on both crystallized and fluid intelligence. This study aimed to determine the effect of functional hearing on verbal reasoning when controlling for age, gender, and education. Additionally, the study investigated whether hearing aid usage mitigated the effect, and examined different routes from hearing to verbal reasoning.

Design: Cross-sectional data on 40- to 70-year-old community-dwelling participants from the UK Biobank resource were accessed. Data consisted of behavioral and subjective measures of functional hearing, assessments of numerical and linguistic verbal reasoning, measures of executive function, and demographic and lifestyle information. Data on 119,093 participants who had completed hearing and verbal reasoning tests were submitted to multiple regression analyses, and data on 61,688 of these participants, who had completed additional cognitive tests and provided relevant lifestyle information, were submitted to structural equation modelling (SEM).

Results: Poorer performance on the behavioral measure of functional hearing was significantly associated with poorer verbal reasoning in both the numerical and linguistic domains ($p < 0.001$). There was no association between the subjective measure of functional hearing and verbal reasoning. Functional hearing significantly interacted with education ($p < 0.002$), showing a trend for functional hearing to have a greater impact on verbal reasoning among those with a higher level of formal education. Among those with poor hearing, hearing aid usage had a significant positive, but not necessarily causal, effect on both numerical and linguistic verbal reasoning ($p < 0.005$). The estimated effect of hearing aid usage was less than the effect of poor functional hearing. SEM analyses confirmed that controlling for education reduced the effect of functional hearing on verbal reasoning, and showed that controlling for executive function eliminated the effect. However, when computer usage was controlled for, the eliminating effect of executive function was weakened.

Conclusions: Poor functional hearing was associated with poor verbal reasoning in a 40- to 70-year-old community-dwelling population after controlling for age, gender, and education. The effect of functional hearing on verbal reasoning was significantly reduced among hearing aid users and completely overcome by good executive function skills, which may be enhanced by playing computer games.

Keywords: hearing, hearing aids, verbal reasoning, education, gender, epidemiology, executive function, computer games

Introduction

Verbal reasoning (VR) refers to the ability to analyze and understand verbal information, whether provided in written or oral form, and to think constructively. Acquisition of knowledge and the ability to store information in semantic long-term memory are two of the underlying processes of verbal performance (e.g. Hunt, 1978), while working memory is engaged in the constructive thinking, or reasoning, process (Salthouse et al., 1989; Kyllonen & Christal, 1990; Süss et al., 2002; Kane et al., 2004). In other words, VR relies on both fluid (working memory processing) and crystallized (knowledge-based judgement) skills (Cattell, 1963). In particular, fluid abilities may include such executive functions as updating, shifting, and inhibition (Miyake et al., 2000), while crystallized abilities are related to the application of knowledge stored in episodic and semantic long-term memory (Tulving, 1987). Complex span tests typically used to measure individual differences in working memory capacity tap into both fluid and crystallized abilities. For example, the Reading Span Test (Daneman & Carpenter, 1980; Rönnberg et al., 1989) requires skilled judgment based on knowledge stored in semantic long-term memory as well as executive processing of episodic memories. Thus, VR is closely related to working memory both conceptually and functionally.

As described by the working memory model of Ease of Language Understanding (ELU; Rönnberg et al., 2013), listening under adverse conditions requires the engagement of cognitive resources. When the signal is degraded, or there is background noise, speech understanding makes particular demands on limited working memory resources. This means that fewer cognitive resources are available for high-level processing of the message (Rudner & Lunner, 2014). Thus, for individuals with hearing impairment, the ability to retain in working memory spoken items heard in noise, even at very favorable signal-to-noise ratios, and transfer them to long-term memory is related to individual working memory capacity (Rudner et al., submitted). The long-term influence on cognitive systems of this constant pressure on working memory during speech understanding for individuals with hearing impairment is poorly understood. However, there is some suggestion that it may be mitigated by hearing aid use (Ng et al., 2014; Rönnberg et al, 2014).

A number of population studies have shown that lifespan trajectories of fluid and crystallized intelligence differ. Fluid intelligence decreases in old age while crystallized intelligence is maintained (Ghisletta & Lindenberger, 2004; Kaufman et al., 2009). Kaufman et al. (2009) also showed that while education significantly influenced both abilities, gender did not influence either. The effect of hearing loss on fluid and crystallized intelligence is less well understood. Lehrl & Seifert (2003) suggested that acquired hearing loss may lead to impairment of fluid intelligence and that in the long term, such a loss can also reduce crystallized abilities. However, Rönnberg et al. (2011) showed that a greater degree of hearing loss was associated with poorer episodic and semantic long-term memory (crystallized abilities) but not with working memory (fluid ability) in a Swedish population, and similar results have been reported in a large British population (Rönnberg et al, 2014). Thus, the impact of hearing loss on VR is likely to depend on the extent to which the specific VR task places demands on the individual's fluid and crystallized intelligence.

In this paper, we investigated the effect of hearing loss on VR ability when controlling for age, gender, and education. For this purpose, we used data from the UK Biobank resource, which includes behavioral and subjective measures of functional hearing and a measure of VR in a sample of over 100,000 community-dwelling volunteers aged between 40 and 70 years. The VR data consisted of multiple choice responses to written questions presented sequentially during a two-minute period, with numerical problems interleaved with problems that required linguistic skills. Both the numerical and linguistic problems required fluid skills as well as crystallized knowledge within the relevant domain, making it hard to predict whether or not hearing loss would have an effect on VR across domains. We further investigated the effect of hearing aid usage on the relationship between functional hearing and VR. Findings from Kaufman et al. (2009) showed that both numerical and linguistic performance was influenced by education, while age and gender exerted an appreciable effect only in the numerical domain. On this basis, we predicted that a higher level of education would be associated with better numerical and linguistic VR performance, and that we would see better performance in the numerical domain among males and younger individuals.

Structural equation modelling (SEM), a technique for analyzing theoretical models of how different variables are related to each other, was used to investigate various pathways between functional hearing and VR. The four latent variables included in these analyses were somewhat opportunistic: the observed measurements forming the latent variables were not specifically selected for this purpose, but were available among a large range of demographic and lifestyle measures in the UK Biobank resource. Two of the latent variables were education and executive function, which were chosen to investigate the extent to which they would confound (i.e. distort) or mediate (i.e. carry) an association between functional hearing and VR. The other two latent variables, social engagement and computer use, were selected based on the notion that social isolation may lead to cognitive decline (Lin et al., 2011), and previous findings that playing video games has been associated with enhanced visuospatial skills (Bavelier & Davidson, 2013) and improved cognitive control in the ageing brain (Anguera et al., 2013).

Methodology

Sample: The UK Biobank resource offers epidemiology data collected on over 500,000 individuals residing in the UK. Participants who were born outside of the UK and the Republic of Ireland and who performed significantly more poorly on the VR test were excluded from the sample to reduce sociocultural effects on the results of the cognitive tests.

Of the remaining population, 119,093 participants had completed testing on hearing and VR and had provided information about age, gender, and education. This sample was used to address the main questions about the effect of functional hearing on VR and whether hearing aid usage mitigates the effect. A sub-sample of 61,668 participants who had completed additional cognitive tests and answered a wide range of questions about health and lifestyle were used in the SEM to investigate different pathways between functional hearing and VR. Table I summarizes the basic statistics for the relevant test variables for each population.

Procedure: People who accepted the invitation to participate in the UK Biobank data collection attended one of 20 assessment centers spread across the UK. All data used in this study were obtained through a self-administered program running on a computer with a touch screen that collected responses to questionnaires and tests on hearing and cognition. All cognitive tasks were based on visual information only, meaning that there was no confounding effect of hearing on these measures. A trained staff member was always present and available for consultation while a participant completed the self-administered program.

The core scientific protocol and operational procedures of the UK Biobank resource, as well as its proposed uses, have approval from appropriate ethics committees in accordance with guidance from the Central Office of Research Ethics.

Hearing measures: Two measures of functional hearing were obtained, one behavioral and one subjective. Both measures related to listening in noise. As a behavioral measure of functional hearing, the participants completed a digit triplets test (Smits et al., 2004). In this test, sets of three random digits were presented in speech-shaped noise under headphones to the unaided ears. The volume of the speech was set to the individual’s most comfortable level for each ear. After the presentation of each triplet, participants entered the three digits heard on a simulated keyboard on the touch screen (forced choice). If the triplet was correctly identified, the noise level was increased; otherwise, the noise level was decreased. The resulting speech reception threshold in noise (SRTn) was the signal-to-noise ratio (SNR) arrived at after 15 presentations. The SNR could vary between -12 and +8 dB. Each ear was tested separately and a better ear SRTn (BESRTn) was obtained for each participant and used as a continuous variable for measured functional hearing in the further analysis. For those who completed the test on only one ear, it was assumed that this was the better ear. Mean performances for the two test samples are provided in Table I. Using the cut-off SNRs reported by Dawes et al. (2014), about 91% of the study sample performed in the 'normal' range (BESRTn < -5.5 dB), while 8% performed in the 'insufficient' range (BESRTn from -5.5 to -3.5 dB, incl.) and 1% were within the 'poor' range (BESRTn > -3.5 dB). The 9% who performed outside the 'normal' range is similar to the 14% of the slightly older cohort (55-74 year olds) in the UK who have a bilateral hearing impairment of at least 35 dB HL (Davis et al., 2007). Among those performing in the 'poor' range, the median performance value was -2 dB SNR and the 90 percentile range spanned 11 dB, suggesting that there was sufficient variation in SNRs among these participants to warrant further analysis.

As a measure of subjective functional hearing, participants responded to a direct question about having hearing difficulty in noise: "Do you find it difficult to follow a conversation if there is background noise (such as TV, radio, children playing)?" The yes/no response distribution is given in Table I. A Spearman rank-order correlation analysis yielded a significant, but weak, relationship between the continuous behavioral measure (BESRTn) and the dichotomized self-reported measure of functional hearing on the large study sample ($R = 0.13$; $p < 0.01$), suggesting some inconsistencies between the two measures of functional hearing.

Participants also provided a yes/no response to a question on hearing aid usage: "Do you use a hearing aid most of the time?" As shown in Table I, only 2.4% gave an affirmative answer to this question. This proportion is a fraction lower than the 3.0% seen in the entire UK Biobank sample, which corresponds to the reported hearing aid intervention rate of 3% among 55-74 year olds in the UK (Davis et al., 2007).

Verbal reasoning: The test used to assess VR consisted of 13 multiple choice questions, of which as many as possible had to be answered within two minutes. Of the 13 questions, seven presented numerical problems, including such tasks as numeric addition, identification of the largest number, positional arithmetic, conditional arithmetic, chained arithmetic, arithmetic sequence recognition, and square sequence recognition. The remaining six questions addressed linguistic skills and included questions on word interpolation, family relationship calculation, synonyms, concept interpolation, antonyms, and subset inclusion logic. The questions, response options, and test instructions can be found in Supplemental Digital Content 1. Participants could skip a question as they proceeded through the test, but could not return to a skipped question later in the test.

The percentage of correct answers given in two minutes to the numerical questions became the numerical VR variable (Numerical VR); the linguistic VR variable (Linguistic VR) represents the same results for the linguistic questions. Study participants attained slightly lower scores in the linguistic domain (Table I); this is likely due to some participants running out of time, as the questions were always presented in the same order and the last question was on linguistic reasoning.

Other independent variables: Other independent variables obtained from the UK Biobank included such demographic variables as age, gender, and education. For education, participants were asked which of the following six qualifications they had obtained: University or College degree or equivalent (Degree), Advanced levels or equivalent (A-levels), Ordinary levels or General Certificate of Secondary Education or equivalent (O-levels), Common Certificate of Education or equivalent (Common), National Vocational Qualification or Higher National Diploma or Higher National Certificate or equivalent (Vocation), or Other professional qualifications, e.g. nursing or teaching (Other). While the UK qualification structure suggests a hierarchical order between the first four categories of qualifications, the last two categorized qualifications (Vocation and Other) were more difficult to place. This is because vocational qualifications can be obtained at any level from the Common Certificate of Education to the doctoral level, but this information was not obtained. The examples given for other professional qualifications suggest that this category included education based on both a theoretical and practical component, where the theoretical component most likely varied in degree. For simplicity, the responses were consolidated into one variable on the highest level of education that assumed that Degree > A-levels > O-levels > Common > Vocation > Other. On all three demographic variables (see Table I), both samples were representative of the UK Biobank resource population.

As part of the assessment, participants also answered questions on computer usage and social engagement and completed cognitive tests tapping into executive function. Two questions asked about computer usage: "In a typical day, how many hours do you spend using the computer? (Do not include using a computer at work)?" and "Do you play computer games?" The response options for the latter question were: never/rarely, sometimes, or often, which were assigned scores from 0 to 2. Responses to the former question were highly skewed and consequently log-transformed. These two parameters are henceforth referred to as PCUse and PCGames, and were used to form a latent variable representing computer usage. Information about social engagement was obtained through questions about frequency of friend/family visits and number of social activities engaged in (including sports club, pub/social club, religious group, adult education, and other group activity). As very few indicated that they were engaged in more than three activities, the scores for this variable were transformed to four categories, indicating no (0), one (1), two (2), or 3 or more (3) activities. The response options to the question on visits were: never or almost never, every few months, once a month, once a week, 2-4 times/week, and daily, which were assigned scores from 1 to 6. These two measures provided the observed variables to a latent variable representing social engagement. For the mean transformed time spent on a computer and the distribution of responses to the questions on playing computer games and social engagement, see Table I.

Finally, participants completed a visuospatial memory test and a visuospatial prospective memory test. Visuospatial memory was measured with a pair matching card game. Participants were presented with six pairs of cards on the computer screen for 5 sec. The pictures were then turned over and the participants were asked to identify as many pairs as possible in the fewest tries. The score was the number of incorrect matches. Due to a skewed distribution of responses, the measure was log-transformed. The mean value is listed in Table I. To measure visuospatial prospective memory, participants were introduced to four symbols at the beginning of the cognitive test session. They were told that at the end of the session they would be presented with the same four symbols and asked to touch the “blue square”, but that they should actually touch the “orange circle” instead. Participants were categorized according to whether they remembered to touch the correct symbol at the first attempt or not. The distribution of responses can be seen in Table I. Both tests required processing with the executive mechanism to coordinate storage of verbal information in short-term or long-term memory, and to update information in memory or combat interference. For example, in the case of the card-sorting test, the symbols on the cards were likely translated to verbal names to be held in short-term memory, and as new cards were turned over, stored information in memory needed to be updated accordingly. In the prospective long-term memory test, verbal instructions and the verbal names of the symbols had to be processed and then stored in long-term memory, and the misleading instructions provided at the end of the test ignored.

Performance on each test was only weakly associated with numerical and linguistic VR ($r < -0.2$). Outcomes on the two tests were used as observed variables to a latent variable labelled executive function.

Data analyses

To determine the association between functional hearing and VR, four regression analyses were performed, using the Numerical VR and Linguistic VR measures as dependent variables and each of the two measures of functional hearing as independent variables, controlling for the effects of age, gender, and education. Interaction effects between functional hearing and age, functional hearing and gender, and functional hearing and education were included by entering the products of these variables as additional independent variables. As a linear relationship between categories of qualifications in the education variable could not be assumed, this parameter was entered as five dichotomous independent variables in the regression analyses. The significance of all effects was determined with a multiple degree of freedom test. That is, a test of the overall effect of each variable (or interaction) was performed by testing the null hypothesis that the parameters involving that variable (or interaction) are all equal to zero. Due to the large number of observations, an a priori p-value of 0.01 was chosen for significance on all statistical tests. Because the interaction effects were relatively small, overall effect sizes were estimated by averaging the estimated effects for all combinations of discrete variables when using mean values for the continuous variables. In these calculations, the effect for each combination of discrete variables was weighted with the sample size of that combination.

To establish the effect of hearing aid usage on any association between functional hearing and VR, the regression analyses were repeated, adding hearing aid usage and the interaction between hearing aid usage and functional hearing as independent variables.

To investigate different pathways between functional hearing and VR, SEM was performed with LISREL 8.80 (Jöreskog and Sörbom, 1993) using a covariance matrix as input. The root-mean-square error of approximation (RMSEA), the comparative fit index (CFI), and the standardized root-mean-square residual (SRMR) were used to evaluate the models' goodness of fit to data. The χ^2 is also reported, but the associated p-values that consistently showed significance of all models due to the large number of observations are not given.

Results

Effect of functional hearing on verbal reasoning: The significance levels for the effects of the subjective and behavioral measures of functional hearing and their interactions with age, gender education on Numerical VR and Linguistic VR are summarized in Table II. Using the regression equations, Figure 1 shows the predicted interaction effects between functional hearing, gender, and highest level of education in the numerical and linguistic domains. In this figure, the estimated effect of self-reported functional hearing is the difference between reporting having or not having difficulty hearing, while for BESRTn the estimated effect corresponds to a 10 dB change in dB SNR, which is the difference between performing roughly in the middle of the normal (-9 dB SNR) and poor (1 dB SNR) ranges of the hearing test.

Analyses involving the subjective measure of functional hearing as the independent variable showed no significant association between functional hearing and Numerical VR ($p = 0.17$) or Linguistic VR ($p = 0.20$), and no significant interactions between functional hearing and age ($p = 0.08$ for Numerical VR, and $p = 0.08$ for Linguistic VR), functional hearing and gender ($p = 0.12$ for Numerical VR, and $p = 0.66$ for Linguistic VR), or functional hearing and education ($p = 0.17$ for Numerical VR, and $p = 0.26$ for Linguistic VR). The negligible effect sizes between those reporting having and not having difficulty hearing in noise were estimated to be -0.03% (Std Err = 0.10%) in the numerical domain and -0.08% (Std Err = 0.11%) in the linguistic domain.

When using the behavioral BESRTn as independent variable, the association between functional hearing and both Numerical VR and Linguistic VR showed significance ($p < 0.001$ in both domains). The effect sizes were for a change in BESRTn of 10 dB estimated to be -7.4% (Std Err = 0.31%) and -6.4% (Std Err = 0.35%) in the numerical and linguistic domains, respectively, confirming that those who performed poorly on the hearing test also were likely to perform poorly on the VR test. There was a significant interaction between functional hearing and education in both domains ($p < 0.001$ for Numerical VR, and $p = 0.004$ for Linguistic VR). In both domains, the effect of functional hearing was greatest among those with ‘other’ and higher levels of education and smallest for those with a Common Certificate of Education. No other interaction effects reached significance.

Generally, education had a strong independent and significant effect on VR ($p < 0.001$ in both domains), with performance predicted to be better for those with a university or college degree. Note that the predicted performance for both Numerical VR and Linguistic VR decreased systematically from the qualifications ‘degree’ to ‘common’ (by, on average, a total of 19.1% and 17.3%, respectively), after which there was a predicted increase in performance. This finding supports the assumption outlined above, that participants holding a vocational qualification or equivalent, or who completed another professional qualification, on average, held a qualification higher than at least the Common Certificate of Education. Gender and age also contributed significantly to Numerical VR ($p < 0.001$), with males and older participants performing better. The estimated effect size between categories of gender was 4.6% (Std Err = 0.09%), while the estimated effect size for a change in age of 10 years was 0.6% (Std Err = 0.06%).

Overall, the results suggest that the behavioral measure of functional hearing has independent associations with Numerical VR and Linguistic VR, with lower VR predicted for those with poorer functional hearing. The effect was similar across domains, and in both domains functional hearing interacted with education. Generally, the data were characterized by a strong effect of education on both Numerical and Linguistic VR, and an additional effect of gender and age on Numerical VR.

Effect of hearing aid usage: The mitigating effect of hearing aid usage was only investigated on the significant association between the behaviorally measured functional hearing variable (BESRTn) and VR. The regression analyses revealed a significant independent effect of hearing aid usage in both the numerical ($F(2,119075) = 5.5$; $p = 0.004$) and linguistic ($F(2,119075) = 5.9$; $p = 0.003$) domains. In both domains, the interaction between hearing aid usage and BESRTn contributed significantly to the prediction of the dependent variables ($F(1,117672) > 8.3$; $p < 0.004$). Figure 2 shows the interaction effect when the difference in BESRTn was 10 dB. As can be seen in this figure, among those who performed in the poor range on the functional hearing test, both Numerical VR and Linguistic VR were predicted to be poorer for non-users than for users of hearing aids. The effect size between categories of hearing aid usage for those performing poorly on the functional hearing test was 2.7% for Numerical VR and 3.1% for Linguistic VR, which are less than half of the effect of functional hearing on VR. In summary, findings suggested an association between hearing aid usage and VR among those who performed in the poor range of the functional hearing test, with those using hearing aids performing better than non-users.

Mediating and confounding effects: SEM was used to further explore the association between the behavioral measure of functional hearing (BESRTn) and VR, taking latent variables on executive function (visuospatial memory, visuospatial prospective memory), computer use (PCUse, PCGames), and social engagement (Visits, Activities) into consideration. For this purpose, a latent variable was created to represent VR, using the Numerical VR and Linguistic VR as observed variables. Table III shows the standardized solution for the measurement model. The goodness of fit statistics show a reasonable fit to data (RMSEA = 0.04; CFI = 0.95; SRMR = 0.024). However, it should be noted that with the selected observed variables, only 11% and 14% of variance was explained in the executive function and social engagement latent variables, respectively, while 60% and 31% of the variance was explained in the VR and computer use latent variables, respectively.

Based on this measurement model, several structured models were tested. First, on the reduced number of observations, SEM showed an acceptable fit of data to the straightforward model assuming that poorer functional hearing is associated with poorer VR (model 1 in Table IV). The standardized regression coefficient of -0.10 is not large, but it is statistically significant due to the high number of observations.

It was hypothesized that each of the independent latent variables, as well as age and education, may also be directly associated with VR. To compare the strength of the association between each of these variables, including hearing, and VR when holding the others constant, the six parameters were tested against each other in model 2. As can be seen from Table IV, the model was a reasonable fit to the data, and suggested that executive function, age and education each had relatively strong significant associations with VR when controlling for the other parameters ($|b| > 0.2$), predicting that older people, and those who have a better education and better executive function performed better on VR. Executive function in particular showed a relatively strong effect on VR ($b = -0.69$). When including these variables, the associations between functional hearing and VR ($b = 0.01$), between computer use and VR ($b = -0.03$), and between social engagement and VR ($b = -0.09$) were rather weak, with the association between functional hearing and VR becoming non-significant.

Given that both education and the executive function latent variable showed strong associations with VR, two hypotheses were then tested: one that considered education as confounder (a factor that distorts the relationship between the independent and dependent variables) and one that considered executive function as mediator (a factor that carries the relationship between the independent and dependent variables) between hearing and VR (Figure 3). As aging is known to be strongly related to both poorer hearing (Cruickshanks et al., 1998; Hartley et al., 2010) and poorer executive function (McCabe et al., 2010), age was controlled for in all variables in the mediation hypothesis. The goodness of fit statistics can be seen in Table IV (models 3 and 4). Both models provided an acceptable fit to data. In model 3, the confounding effect of -0.02 is significant but does not exceed the reduced direct effect between BESRTn and VR (b = -0.07). In model 4, the mediation effect of -0.11 is significant and exceeds the direct, now non-significant, effect between BESRTn and VR (b = 0.0). That is, according to these models, education partially distorts the relationship between BESRTn and VR, as participants with higher levels of education were more likely to have better functional hearing. When controlling for age in all variables, executive function was found to completely carry the relationship between functional hearing and VR: people with poorer functional hearing had poorer executive function and hence performed more poorly on the VR test. The latter model shows an inconsistent effect between age and VR, as the direct effect and the indirect effect between these two variables via executive function have opposite signs. However, it is plausible that although older people are more likely to have poorer executive function and hence poorer VR, they showed better VR ability when executive function is held constant.

Building on model 4, a hypothesis that the executive function mediation effect on the association between BESRTn and VR was spurious due to computer use (e.g. Anguera et al., 2013) was tested in model 5. The model assumed that frequent use of computers enhances executive function, that computers are used more by people with better functional hearing (who are better educated), and that older people, who tend to have poorer functional hearing and executive function, use computers less (Figure 4, full lines). Again, the model was an acceptable fit to the data (cf. Table IV). Including computer usage as a confounder in the model reduced the effects between both functional hearing and executive function and between executive function and VR, meaning that the executive function mediation effect on the relationship between BESRTn and VR was reduced by 0.02. That is, computer usage partially distorted the executive function mediation effect on the association between BESRTn and VR. Note that the association between use of computers and executive function is relatively strong (b = -0.30), suggesting that people who used computers more had better executive function, and that frequency of playing computer games was more highly correlated with the computer usage latent variable than time spent on a computer.

Finally, starting with model 5, education was added as a confounder to the relationship between BESRTn and VR (Figure 4, dashed lines). Combining the two effects further reduced the already negligible and non-significant relationship between BESRTn and VR.

Discussion

Using observations on 119,093 individuals, and controlling for age, gender, and education, this study found that behaviorally measured poor functional hearing had a significant and independent association with poor VR, while self-rated functional hearing did not. The two measures of functional hearing were not strongly correlated with each other, which is in agreement with other reports (Kamil et al., 2015), so a difference in outcomes for the two measures was not surprising. Self-ratings may be particularly influenced by such factors as personality traits and mental health (e.g. Keidser et al., submitted) that would not be expected to impact on VR (e.g. Mowla et al., 2007) and that were not controlled for in this study. The effects of measured functional hearing were estimated for a 10 dB difference in performance on the digit triplets test, which, according to data from Smits et al. (2004), corresponds on average to the difference between normal hearing and a moderately severe hearing loss. The estimated effect size associated with a moderately severe hearing loss was equivalent to missing or incorrectly answering half a question on the VR test, and thus seems rather small. However, given the relatively small proportion of participants in the study sample who performed outside the normal range of the behavioral hearing test, the significant effect is of interest. The finding suggests that the VR test used in this study may depend more on crystallized than fluid skills in both the numerical and linguistic domains, as poor hearing has been found to be negatively associated with episodic and semantic long-term memory in particular (Lin et al., 2011; Rönnberg et al., 2011; 2014).

The study further found that hearing aid usage had a significant mitigating effect on the association between behaviorally measured functional hearing and VR. The effect was of similar size for the numerical and linguistic domains, and was smaller (about half the size) than the effect of a significant hearing loss on VR, but is equally notable because of the small proportion of test participants in this study who were hearing aid users. Two points should be noted here. First, only people who used their hearing aids ‘most of the time’ were captured with the direct question on hearing aid usage, which could enhance the effect. In other words, if a potential protective effect of hearing aid usage on VR skill depends on hearing aids being used extensively, we would expect to see a weaker effect if also including part-time users of hearing aids in the analyses. Consequently, this finding is not directly applicable to hearing aid usage in general. Second, the mitigating effect of hearing aid usage was only observed among users who performed poorly on the hearing test, which suggests, and not unreasonably so, that the device seems to have a protective role only if the hearing problem significantly affects unaided functional hearing. The finding that a small proportion of hearing aid users performed in the normal range of the hearing test is plausible. Validation data on a digit triplets test (Smits et al., 2004) showed a relatively high correlation of 0.77 between performance on this behavioral test and the average pure-tone hearing loss (measured across 0.5, 1, 2, and 4 kHz), but also that it is possible for some people with an average pure-tone hearing loss up to about 50 dB HL to perform in the defined normal range. Overall, our finding agrees with previous suggestions that hearing aid usage may slow cognitive decline among hearing-impaired people (Cacciatore et al., 1999; Lin, 2011). Unfortunately, as data in this and previous studies were cross-sectional, the temporal order cannot be firmly established. Therefore, it is uncertain whether hearing aid usage really improved VR ability, or if people with better VR were more likely to have obtained hearing aids. This effect must be further investigated in a longitudinal data set.

As predicted, both regression analyses and SEM showed that education had a significant association with VR, with those with higher levels of qualification performing better on the VR test in both the numerical and linguistic domains. This is in agreement with findings in the general population that VR is significantly associated with academic achievements (Gustin & Corazz, 1994; Deary et al., 2007), and that both fluid and crystallized abilities increase with increasing education (Kaufman et al., 2009). As shown with the SEM, the effect of functional hearing on VR was reduced when controlling for education, suggesting that lower levels of education were also associated with poorer functional hearing. A significant association between education and hearing loss has been observed in other epidemiological studies (Cruickshanks et al., 2010; Kiely et al., 2012). Low education is an indicator of low socioeconomic status and is linked with noisy work environments, poor health behaviors, and increased stress.

This study further suggested a significant interaction between functional hearing and education, with functional hearing having a greater effect among those who had obtained higher levels of education. The interaction effect was due to a smaller effect of education on VR performance observed among those who performed more poorly on the behavioral hearing test. Level of education is one of the key predictors of brain maintenance (Nyberg et al., 2012). This concept refers to the phenomenon that individual differences in the manifestation of age-related brain changes and pathology allow some people to show little or no age-related cognitive decline. Our findings suggest that poor functional hearing may undermine the key influence of education on brain maintenance.

The significant gender effect in the numerical domain was predicted and is in agreement with observations by Kaufman et al. (2009) and findings from a meta-analysis by Hyde et al. (1990), which show that beyond high school, males outperform females on problem-solving tasks. Hyde et al. (1990) speculated that this was partly because males were more likely than females to choose mathematics courses during post-secondary education. It could also be speculated that the numerical questions in the VR test required more fluid processing relative to the linguistic questions, in which case findings tie in with demonstrated male advantages on working memory tasks in a meta-analysis by Meinz & Salthouse (1998). In support of this hypothesis, males in this study sample did perform significantly better than the females on the two measures that make up the executive function latent variable.

As predicted, age had a significant, albeit very small, effect on Numerical VR, but not on Linguistic VR. However, while Kaufman et al. (2009) observed that younger people performed better than older people on a mathematical test, the older participants in this study outperformed the younger participants on the numerical questions. This discrepancy could be due to the types of problems presented in the two tests. It is also possible that the introduction of handheld and pocket calculators in the 1970s may have had a negative effect on the ability of the younger participants, in particular, to quickly recognize number patterns and manipulate numbers in their head. According to a meta-analysis conducted by Ellington

(2003), however, problem-solving skills in precollege students were not hindered by the inclusion of calculators in mathematics instruction, at least not in the short term.

SEM analyses demonstrated that executive function, which influences fluid intelligence skills, had a complete mediating effect on the direct association between functional hearing and VR. This effect suggests a strong link between executive function and VR, with poorer executive function resulting in poorer VR performance (Figures 3 and 4). A moderate correlation between working memory, which is also associated with fluid intelligence, and VR was found by Salthouse et al. (1989), who observed that working memory partially mediated the negative effect of age on VR. Other studies have shown strong relationships between working memory and reasoning ability (e.g. Kyllonen & Christal, 1990; Engle et al., 1999; Süss et al., 2002). Overall, the SEM analysis may suggest that a negative effect of hearing loss on the crystallized functions supporting VR could be outweighed by preserved fluid intelligence. More systematically designed studies are required, however, to reveal the strength of any mediation effect of different cognitive constructs, including fluid and crystallized skills on the effect of functional hearing on VR.

Computer usage, an activity that does not necessarily include auditory stimuli or require good hearing, may improve executive function. Our SEM analyses suggested that using a computer (cf. Figure 4) slightly confounded the mediating effect of executive function on the association between functional hearing and VR. Specifically, when controlling for age, those who used computers more performed significantly better on the tests tapping into the executive function. It should be noted that the effect of computer usage was driven more by the measure of how often participants played computer games than the measure of the time they spent on a computer daily, which excluded computer usage at work. Cognitive plasticity through task-specific training has been widely demonstrated, and has been observed for both younger and older adults (see introduction of Dahlin et al., (2008) for a review). Behavioral and neural transfer effects from custom-designed computerized adaptive training programs to other cognitive abilities are also evident (see Klingberg (2010) for a review). Recently, Anguera et al. (2013) showed that by playing a custom-designed, adaptive, three-dimensional, multi-tasking video game, older adults showed reduced multi-tasking costs compared to both an active and a no-contact control group, with training results extending to untrained cognitive control abilities, including working memory. The multi-tasking gains persisted for 6 months, with attained levels being better than those achieved by a group of untrained young adults. Using electroencephalography (EEG) measurements, the authors also demonstrated increased midline frontal theta power in the training group. The actual activities engaged in while on the computer and the games played by our study sample are unknown, but most likely included the use of social media applications, internet browsing, and commercial games. Nevertheless, the results from this study indirectly support previous findings that specifically designed training programs and computer or video games can stimulate cognitive function. Thus, people with functional hearing problems could be encouraged to engage in such exercises to maintain cognitive controls that otherwise could be affected by constantly listening to degraded input signals.

Finally, the outcomes of this study should be viewed in light of the following limitations related to data collection: 1) The response rate among candidates for the UK Biobank resource was, at 5.4%, low, which means that the study sample cannot be deemed totally random; 2) The relative proportion of participants performing poorly on the hearing test was low, which could influence the effect sizes presented in this paper; and 3) The large number of participants and the wide spectrum of health and lifestyle measures targeted in the resource comes at a cost of administering the multiple comprehensive tests required for a high-impact investigation of a specific research question. For example, the measures of self-reported functional hearing and hearing aid usage were based on a single direct question, the measures of executive function were not obtained with standardized tests, and the measures for the executive function and social engagement latent variables explained less than 20% of variance in those variables.

Conclusion

In a community-dwelling population aged between 40 and 70 years, people with poorer functional hearing performed significantly more poorly on verbal reasoning than people with normal functional hearing when controlling for age, gender, and education, especially among those with high levels of education. SEM suggested that good executive function, which may be enhanced by computer usage (playing computer games in particular), overcomes this effect. Hearing aid usage showed a protective effect among those who had difficulty hearing in noise, but may not be the direct cause of better verbal reasoning performance.

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Table I: Mean and standard deviation values (in brackets) of continuous test variables, and the response distribution for categorised test variables shown for the entire study sample (N = 119,093) and the sub-sample (N = 61,668) used for the structural equation modelling.

Variable	N = 119,093	N = 61,668
Age (years)	56.1 (8.10)	56.1 (8.07)
Gender (female/male ratio)	54/46	51/49
Functional hearing: BESRTn (dB SNR)	-7.5 (1.54)	-7.8 (1.42)
Functional hearing: reported difficulty (yes/no ratio)	35.7/64.3	N/A
Hearing aid usage (yes/no ratio)	2.4/97.6	N/A
Numerical VR (correct % points)	58.9 (16.86)	59.6 (16.71)
Linguistic VR (correct % points)	39.0 (18.33)	39.8 (19.17)
Education (Degree/A-levels/O-levels/	38.8/13.8/26.6/	41.4/13.9/25.4/
Common/Vocation/Other ratio)	7.0/7.8/6.0	6.3/7.4/5.7
PCUse (log(hours/day))	N/A	0.70 (0.49)
PCGames (never or rarely/sometimes/often ratio)	N/A	80.0/17.1/2.9
Visits (never or rarely/every few months/once a	N/A	1.2/6.3/14.4/
month/	N/A	37.2/30.8/10.2
once a week/2-4 times a week/daily)	N/A	27.7/43.1/23.4/5.8
Activities (0/1/2/>3 ratio)	N/A	1.5 (0.63)
Visuospatial memory (log(incorrect matches))		
Visuospatial prospective memory	N/A	84.7/15.3
(correct/incorrect ratio)		

BESRTn = better ear speech reception threshold in noise; VR = verbal reasoning; PCUse = usage of PC; PCGames: playing computer games.

Table II: The significance levels of functional hearing and its interactions with gender, age, and education in the numerical and linguistic domain. The denominator df was 119,077.

	Numerical verbal reasoning			Linguistic verbal reasoning		
Effect	F-value	df	p-level	F-value	df	p-level
Reported functional hearing	1.64	8	0.17	1.37	8	0.20
Reported functional hearing * Gender	2.38	1	0.12	0.19	1	0.66
Reported functional hearing * Age	3.11	1	0.08	3.13	1	0.08
Reported functional hearing * Education	1.56	5	0.17	1.31	5	0.26
BESRTn	77.8	8	< 0.001	47.7	8	< 0.001
BESRTn * Gender	0.72	1	0.40	6.30	1	0.01
BESRTn * Age	1.95	1	0.16	0.004	1	0.95
BESRTn * Education	5.43	5	< 0.001	3.46	5	0.004

BESRTn = better ear speech reception threshold in noise; HLQ = highest level of qualification.

Table III: The correlation coefficients between each observed variable and the selected latent variable with the measurement error (variances) shown in bracket.

Observed variable	Verbal reasoning	Executive function	Computer use	Social engagement
Numerical VR	0.79 (0.37)			
Linguistic VR	0.75 (0.44)			
VSM		0.32 (0.89)		
VSPM		0.31 (0.90)		
PCUse			0.73 (0.47)	
PCGames			0.30 (0.91)	
Visits				0.46 (0.79)
Activities				0.24 (0.94)

VR = verbal reasoning; VSM = visuospatial memory; VSPM = visuospatial prospective memory; PCUse = usage of PC; PCGames: playing computer games.

Table IV: Overview of the models tested with SEM, including the standardised regression coefficient (b) for different paths of the models and their significance level (p), and goodness of fit statistics; the chi-square (χ^2) with degree of freedom (df), the root mean square error of approximation (RMSEA), the comparative fit index (CFI), and the standardised root mean square residual (SRMR).

Model	Path	b	p	χ^2 (df)	RMSEA	CFI	SRMR
1*	BESRTn>VR	-0.10	<0.001	9 (1)	0.012	1.0	0.003
2	BESRTn>VR	0.01	n.s.	2583 (26)	0.040	0.95	0.024
	Age>VR	0.28	<0.001				
	Education>VR	-0.22	<0.001				
	Executive function>VR	-0.69	<0.001				
	Computer use>VR	-0.03	<0.01				
	Social engagement>VR	-0.09	<0.001				
3	BESRTn>VR	-0.07	<0.001	5 (1)	0.008	1.0	0.002
	Confounding effect (Education)	-0.02	<0.001				
4	BESRTn>VR	0.01	n.s.	290 (5)	0.030	0.99	0.013
		-0.11	<0.001				

	Mediation effect (Executive function)						
5	BESRTn>VR Mediation effect (Executive function) controlling for PCUse	-0.01 -0.09	n.s. <0.001	587 (13)	0.027	0.99	0.015
6	BESRTn>VR Confounding effect (Education) Mediation effect (Executive funcction)	-0.00 -0.02 -0.08	n.s. <0.001 <0.001	2111 (18)	0.043	0.96	0.028

BESRTn = best ear speech reception threshold in noise; VR = verbal reasoning;

*) The error variance of verbal reasoning in the linguistic domain set to 0.5 was introduced as constraint in the first model to obtain a df > 0. No constraints were introduced in the other models.

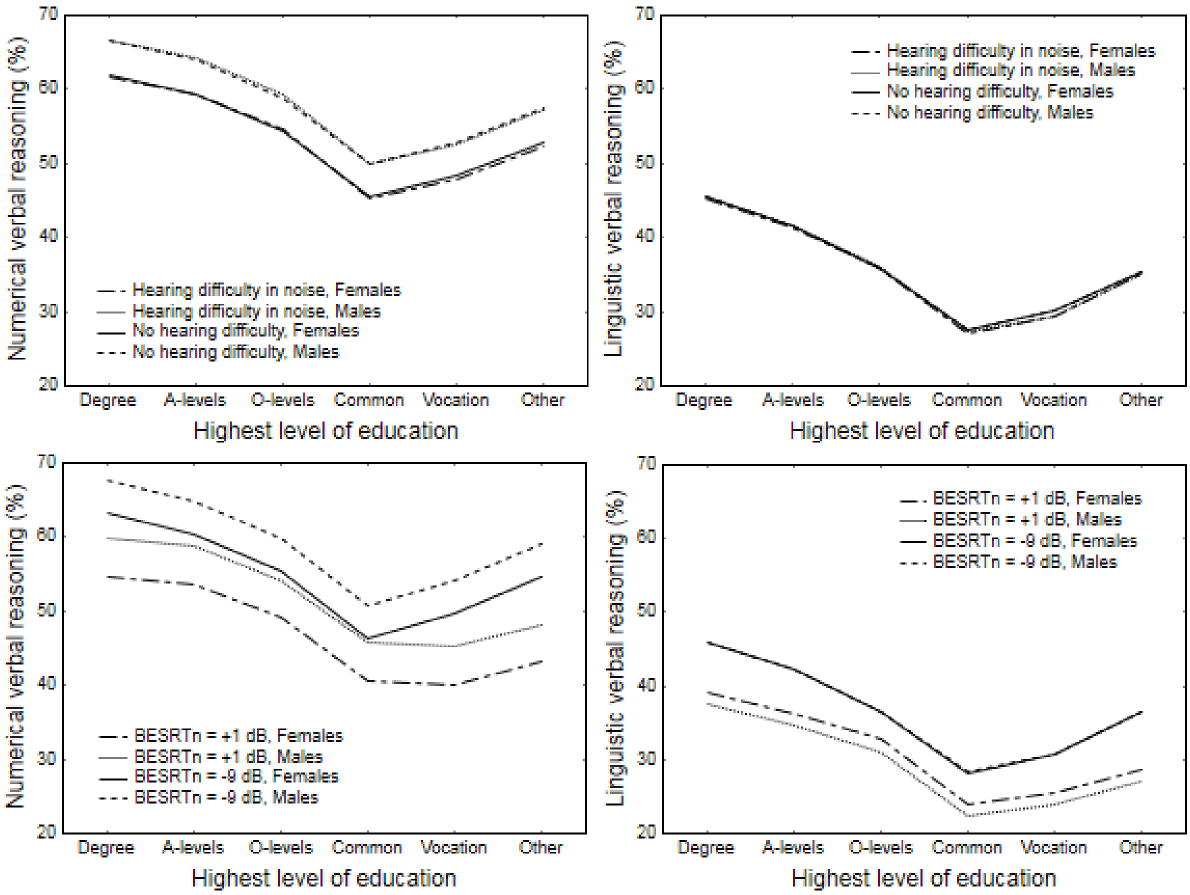
Figure legends

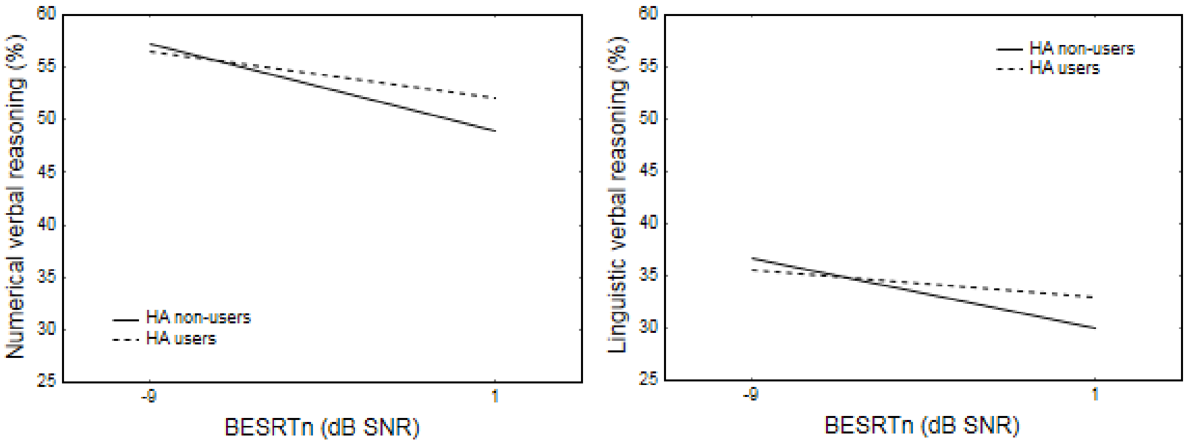
Figure 1: Interactions of functional hearing (reported top, measured bottom) with gender and education for predicted verbal reasoning in the numerical (left) and linguistic (right) domain.

Figure 2: Interactions of hearing aid usage with measured functional hearing for predicted verbal reasoning in the numerical (left) and linguistic (right) domain. HA = hearing aid.

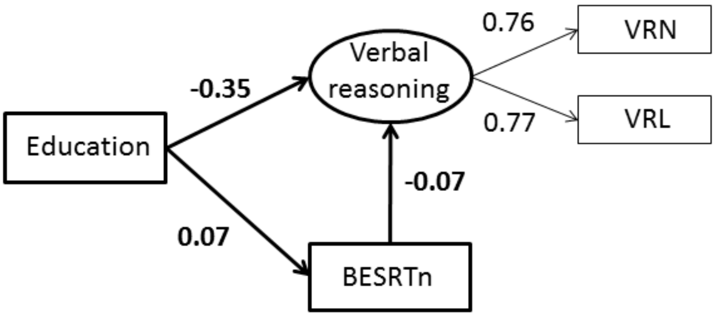
Figure 3: A schematic overview of the structure of models 3 (top) and 4 (bottom) investigating the confounding effect of education and the mediating effect of executive function, when controlling for age, respectively, on the relationship between measured functional hearing (BESRTn) and verbal reasoning. The goodness of fit statistics for the models are provided in Table IV. Path coefficients are standardized values with an (ns) indicating a non-significant path coefficient.

Figure 4: A schematic overview of the structure of models 5 (full lines) and 6 (full and dashed lines). See text for further details. The goodness of fit statistics for the models are provided in Table IV. Path coefficients are standardized values with an (ns) indicating a non-significant path coefficient.

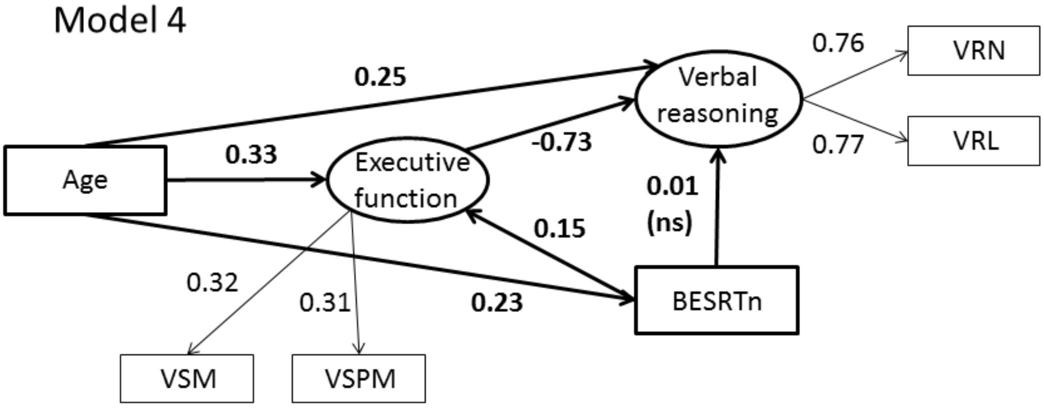

Numerical verbal reasoning (%)
Hearing difficulty in noise, Females
Hearing difficulty in noise, Males
No hearing difficulty, Females
No hearing difficulty, Males
Degree
A-levels
O-levels
Common
Vocation
Other
Highest level of education
Linguistic verbal reasoning (%)
Hearing difficulty in noise, Females
Hearing difficulty in noise, Males
No hearing difficulty, Females
No hearing difficulty, Males
Highest level of education
Numerical verbal reasoning (%)
BESRTn = +1 dB, Females
BESRTn = +1 dB, Males
BESRTn = -9 dB, Females
BESRTn = -9 dB, Males
Highest level of education
Linguistic verbal reasoning (%)
BESRTn = +1 dB, Females
BESRTn = +1 dB, Males
BESRTn = -9 dB, Females
BESRTn = -9 dB, Males
Highest level of education


Numerical verbal reasoning (%)
HA non-users
HA users
-9
1
BESRTn (dB SNR)
Linguistic verbal reasoning (%)
HA non-users
HA users
-9
1
BESRTn (dB SNR)

Model 3



Model 4



Models 5 and 6