The association between cognitive functioning in the elderly and measurement of auditory performance

Master Thesis Clinical Language, Speech and Hearing Sciences
Marianne Resoort, 3046982
Utrecht University

VU medisch centrum

LASA
Longitudinal
Aging
Study
Amsterdam

Supervisors:
T.N. van den Kommer, MSc. and M. Pronk, MSc. (LASA)
Prof. dr. P.H. Dejonckere (Utrecht University)

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ABSTRACT

The purpose of the present study was to investigate the cross-sectional and longitudinal association between cognitive functioning and auditory performance in older persons. Respondents were community-dwelling elderly (age ≥ 65 years). Data were collected as part of the Longitudinal Aging Study Amsterdam (LASA) and were analyzed using multiple regression models (N=1098 of whom N=607 had longitudinal data). Cognitive measures were used to assess general cognitive functioning (Mini-Mental State Examination) (MMSE), information processing speed (Coding Task), fluid intelligence (Raven Coloured Progressive Matrices) and episodic memory (15 Words Test). The Speech-in-noise test (SNT) by Smits et al. (2004) was used to assess auditory performance.

Adjusted cross-sectional models showed a significant negative association between lower levels of cognitive functioning and poorer auditory performance. This means that when cognitive scores are lower, SNT-scores are higher, indicating poorer hearing. The strongest association appeared between the MMSE and the SNT. Adjusted longitudinal models showed an unexpected significant, yet small association between the differences in MMSE-scores and the differences in SNT-scores, which remained absent for other the cognitive tests. This indicates that a decrease in MMSE-score over three years of follow-up is associated with a decrease in SNT-score over three years of follow-up, indicating better hearing, and vice versa. The significant longitudinal association found for the MMSE was unexpected and needs further investigation. All other longitudinal analyses yielded no significant results. The current results suggest that the cross-sectional association between cognitive functioning and auditory performance is evident, but that a longitudinal association between differences seems absent.

Keywords: Auditory performance; Cognitive functioning in elderly; Speech in noise; Longitudinal population-based study

1. Introduction

Due to increased life standards and improved medical knowledge, people around the world are growing older. At the beginning of the twenty first century we are facing the problems that coincide with this trend of global aging. This study focuses on the association between two highly prevalent age-related conditions; age-related hearing loss (presbyacusis) and cognitive decline. The sensitivity of human hearing decreases progressively with age, and higher frequencies are more often affected than lower frequencies (ISO, 2000). Age-induced hearing loss in elderly (≥ 55 years) has an estimated prevalence between 8% and 38%, depending on the definition that is used (Duijvestijn et al, 1999). Cognitive disorders are also becoming increasingly more prevalent. One of the most prevalent diseases that causes cognitive decline, is Alzheimer's disease. Worldwide, 35.6 million people suffer from Alzheimer's disease in 2010 (World Alzheimer Report, 2009). This number is expected to nearly double every 20 years, reaching an estimated number of 115.4 million Alzheimer patients in 2050 (World Alzheimer Report, 2009).

According to Kiessling et al. (2003), globally, three features can be distinguished when considering the processes involved in auditory performance. In the first place, this concerns 'hearing', which is the peripheral functioning of the ear. Hearing entails sensing the acoustic signal in the outer and inner ear, and determining its direction, pitch, loudness and quality. The second feature of auditory performance is 'listening': directing ones attention to a sound and hearing with intention. The third feature is 'comprehension', which entails the central processing of the acoustic signal to receive information, meaning or intent (Kiessling et al, 2003). During this central processing, several active cognitive operations take place in different parts of the brain, for example phonological decoding (to distinguish individual words in the speech stream), lexical selection (to determine which word is perceived) and grammatical decoding (to determine the function of the word in a sentence) (Levelt, 1989). In this study, the term 'auditory performance' is used to describe a person's ability to listen to and comprehend spoken language. Recent studies provide evidence that people with cognitive disorders (e.g. caused by Alzheimer's disease) can experience difficulties with the processing of speech (i.e., comprehension) (Grober & Bang, 1995; MacDonald et al, 2001).

Over the last years there has been increasing evidence for the association between cognition and auditory performance. Since the nineteen eighties, numerous studies on this subject have been published. In 1991, Gennis et al. reviewed fifteen studies and concluded that there seems to be a significant positive association between cognitive functioning and auditory performance in demented patients, but that this association is questionable in normal elderly people (Gennis et al, 1991). The ages in the reviewed studies ranged from 55 to 75 years. This age range is approximately comparable to the age range of the current study. Michael Akeroyd (2008) recently conducted a review, summarizing and discussing twenty studies that have been published since 1989. The age range in the reviewed studies was rather large, since Akeroyd (2008) reviewed six studies that used a sample of younger adults (20 to 34 years). The ages in the other fourteen studies ranged from 64 to 79 years. Although Akeroyd (2008) found varying results, he could conclude that there seems to be an association between cognition and auditory performance. This was found in hearing-impaired non-cognitively impaired persons. However, he mentioned that functional hearing loss remained the strongest predictor of auditory performance. It should be noted that the age range in Akeroyd's study is rather large, ranging from 20 to 79 years. Therefore, it may be possible that his conclusions are not fully applicable to an older study sample.

While cross-sectional associations seem apparent, there is still debate as to the presence of a causative relation and its direction. Some studies focused on the influence of cognition on auditory performance, whereas others assumed an effect of auditory performance on cognition. Valentijn et al. (2005) summarize four hypotheses about the nature of the association between cognitive and sensory functioning. The first is the "sensory deprivation" theory, which claims that after a long period of lacking sensory input, cognition deteriorates because of neural atrophy (Lindenberger & Baltes, 1994; Sekuler & Blake, 1987). The second hypothesis, known as the "resource allocation" theory, states that individuals with sensory problems have to use more attentional resources to identify and process sensory input. Consequently, they have fewer resources left for other tasks that impose large cognitive demands (Baltes & Lindenberger, 1997). A third well known hypothesis is the "common cause" hypothesis, which argues that a third common factor exists that mediates the association between cognition and sensory functioning. A shared age-related change, such as degeneration of central nervous structures, could therefore result in a decline in both sensory functioning and cognition (Anstey et al, 1997; Lindenberger & Baltes, 1994; Christensen et al, 2001). The fourth and final hypothesis states that difficulties in sensory perception cause decline in the performance on neuropsychological and cognitive tests (Lindenberger et al, 2001; Van Boxtel et al, 2001; Rabbitt, 1991; Van

Boxtel, 2000). Furthermore, Akeroyd (2008) hypothesizes that listeners use 'top-down' skills to comprehend speech and to resolve any missing or confusing signals. This assumption is explained more extensively in the CHABA (1988) report. This report states that listeners use their knowledge of the world, their understanding of syntax and semantics and their understanding of the rules of conversation to segment the continuous acoustic stream into phonemes, syllables, words and sentences (CHABA report, 1988). From this perspective, it can be hypothesized that when cognition deteriorates, and knowledge of the world, understanding of syntax and semantics, and understanding of the rules of conversation is no longer readily available, the listener will experience greater difficulties with the segmenting and comprehension of the speech stream.

It is difficult to compare different studies on the association between auditory performance and cognitive functioning, because of the large range of both cognitive tests and hearing tests that are used. Akeroyd (2008) found at least 7 categories of hearing tests (sentences, words, syllables, phonemes, babble, noise and quiet). As far as the cognitive tests are concerned, Akeroyd (2008) reported a total number of 27 different cognitive tests that were used in the twenty reviewed studies. Since there is such an abundance of tests, it is likely that the usage of different tests will yield different results as to the association between cognition and hearing (Akeroyd, 2008).

Although Akeroyd (2008) reported that much of the variety in findings could be due to the different cognition and hearing measures that were used, he could draw some tentative conclusions regarding the constructs of cognition and hearing that seemed to be related. The tests with the strongest predictive character seemed to be those measuring working memory. The least sensitive tests were those that measured a general ability like Intelligence Quotient (Akeroyd, 2008), although there have been studies that found significant results using this type of measurement (e.g. Humes, 2002; Humes et al, 2006). Regarding hearing status measures, most significant effects were found when sentences in noise were used. Furthermore, Akeroyd (2008) claimed that measuring comprehension of speech would yield stronger results than solely measuring the identification of speech, because the first would be more cognitively demanding.

Most of the existing studies on cognition and auditory performance are cross-sectional. Only few have chosen a longitudinal approach to study the effects (Uhlmann et al, 1986; Peters et al, 1988). Uhlmann et al. (1986) found that hearing-impaired respondents had a mean decline of 3.9 points on the Mini-Mental State

Examination (MMSE) (Folstein et al, 1975) over 1 year of follow-up, versus a mean decline of 2.2 points in the normal-hearing respondents. Peters et al. (1988) found that their hearing-impaired group declined 5 points on the MMSE over 9 months of follow-up, in comparison to a 1 point decline in the normal-hearing group. These two studies used 'the ability to hear finger friction at 2 cm' (Uhlmann et al, 1986) and pure tone audiometry (Peters et al, 1988) to determine hearing status. However, these mainly measure peripheral functioning (i.e., 'hearing'), and hardly address intensive central processing required more strongly for speech comprehension. In addition, this concerned a hearing-impaired versus a normal-hearing population. The association may not apply in a general sample.

The purpose of the present longitudinal population-based study was to examine the association between four cognitive tests (measuring general cognitive functioning, information processing speed, fluid intelligence and episodic memory) and a speech-in-noise test (SNT) in older persons. To this end, both the cross-sectional and longitudinal association (three year follow-up) between these measures was investigated, using a large population-based data set of older persons. It is hypothesized that 1) poorer baseline cognition will be associated with poorer baseline auditory performance scores; 2) absolute deterioration over time in cognition will be associated with absolute deterioration over time in auditory performance; 3) poorer baseline cognition will be associated with absolute deterioration in auditory performance.

2. Methods

2.1 Study sample

For the current study, data were used from the Longitudinal Aging Study Amsterdam (henceforth: LASA). These data were collected for an ongoing population-based longitudinal study. The respondents in the LASA project were elderly inhabitants of three geographic areas in the Netherlands. Initial ages of the respondents were 55-85 years and respondents were stratified by age, gender and expected 5-year mortality rate. Respondents took part in a main interview and a medical interview, which were conducted by trained and closely monitored interviewers and by nurses, respectively. The study was approved by the Ethical Review Board of the VU University Medical Center (VUmc) and all respondents gave their informed consent. Further details about the sampling and data collection have been described by Deeg et al. (2002).

A total number of 3107 respondents were initially enrolled in the LASA study (1992/1993), and follow-up measurements were administered every three years. A flow chart of the study sample and main reasons for loss-to-follow-up are presented in Figure 1.

In the current study, data of two follow-up measurement waves were used. During the third follow-up measurement (2001/2002, henceforth T1 or baseline) 1474 respondents participated in the medical interview, in which the Speech-in-noise test (SNT) (Smits et al, 2004) was included. For the cross-sectional analyses, 1098 respondents were included. These respondents had completed the SNT in the third follow-up measurement (T1) and also completed one or more cognitive tests. During the fourth follow-up measurement (2005/2006, henceforth T2) a total number of 1805 respondents participated in the medical interview. For the longitudinal analyses, 607 respondents were included. They had completed the SNT both on T1 and T2 and also completed one or more cognitive tests on both follow-up measurements. A total number of 491 respondents (44.7%) did not complete the SNT on T2. From these 491 respondents, medical interview data (T2) were available for 316 respondents (28.8%). 140 respondents died (12.7%), 20 respondents refused to participate (1.8%), 10 respondents were ineligible (0.9%) and 5 respondents could not be contacted (0.5%). A random sample of 38 respondents was drawn to see which were the main reasons for not having an SNT-score (Pronk, unpublished). It appeared that the main reasons for not completing the SNT seemed due to practical problems (e.g., unavailability of accessible telephone socket) or technical difficulties with the testing equipment.

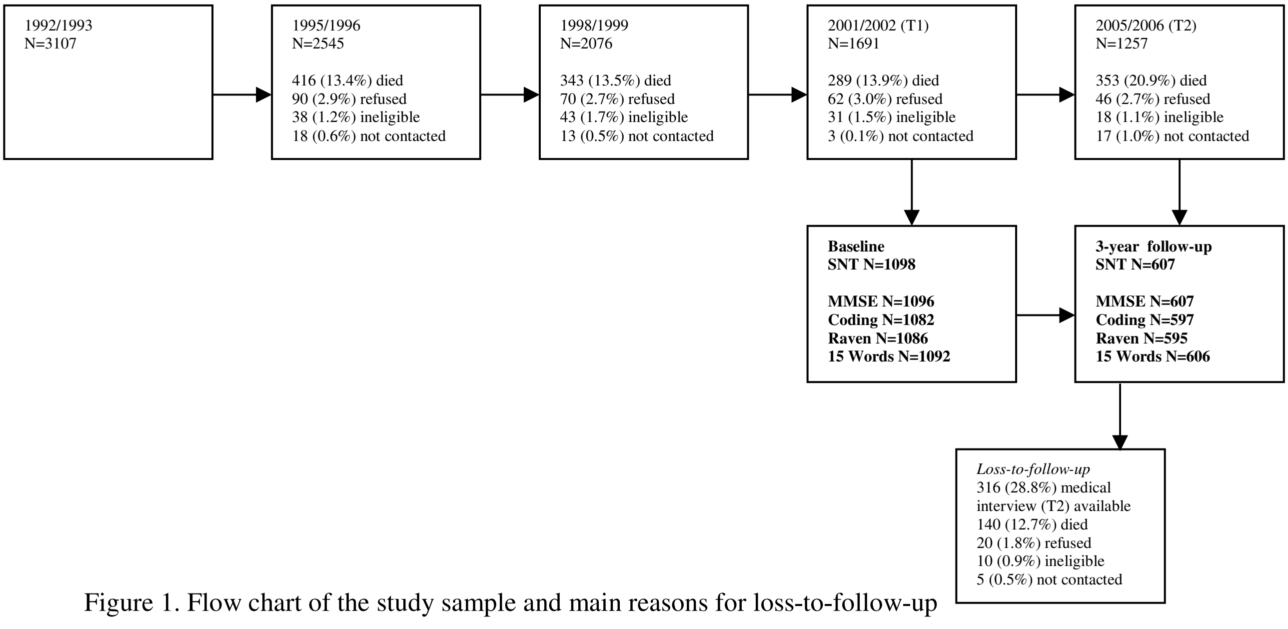

Figure 1. Flow chart of the study sample and main reasons for loss-to-follow-up

Differences in baseline characteristics between respondents on the medical interview (T1) and respondents that completed the SNT (T1) were tested with the *t* test for normally distributed data and the Mann-Whitney *U* test for skewed data. Respondents that participated in the medical interview but did not complete the SNT (*n*=376), were significantly older (79.3 vs. 74.7 years), were less educated (8.6 vs. 9.3 years), had poorer vision (2.6 vs. 2.3) and wore a hearing aid more often (18.1% vs. 10.7%). The respondents that did not complete the SNT also had significantly lower scores on the MMSE (25.1 vs. 27.4), the Coding Task (21.5 vs. 24.6), the Raven Coloured Progressive Matrices (16.6 vs. 18.2) and the 15 Words Test (7.2 vs. 8.8). All differences were significant at the $p \leq .001$ level.

2.2 Measures

2.2.1. Independent variables

General cognitive performance was measured with the Mini-Mental State Examination (MMSE) (Folstein et al, 1975), a short screening method that is widely used to detect cognitive impairment. It consists of 20 items (questions and assignments) and scores range from 0 to 30 (higher scores indicate better cognitive functioning).

Information processing speed was measured with an adapted version (Piccinin & Rabbitt, 1999) of the Alphabet Coding task-15 (Savage, 1984). In the Coding Task, respondents are shown two rows of characters, each character in the upper row belonging to a character in the bottom row. The test condition also consists of two rows, one row contains characters and the other one is empty. The respondent has to make as many correct combinations of characters as possible by naming the corresponding character. This test was administered in three cycles of one minute. In this study, the mean score of the three trials is used in the analyses. Mean test scores range from 1.0 to 42.7 (higher scores indicate better information processing speed).

Fluid intelligence was measured with the Raven Coloured Progressive Matrices (RCPM) (Raven, 1995), which measures how respondents process new information. Each respondent is presented visually with 2 x 12 items. Each item contains a drawing (matrix) of a pattern from which a section is missing. On the bottom of the presented page, six patterns are printed that are possible matches with the matrix. The respondent has to select the best fitting pattern to match the matrix. For each correct response, one point is assigned. Therefore, total scores range from 0 to 24 points.

The 15 Words Test, a Dutch translated version of the Auditory Verbal Learning Test (AVLT) (Rey, 1964; Deelman et al, 1980; Saan & Deelman, 1986), was used to measure episodic memory. In this test, the respondent is presented with 15 words that have to be learned and reproduced in three trials. After each trial, the respondent has to recall as many words as possible. Recall scores range from 0 to 45 words (3 trials * 15 words). In this study, the maximum recall score of the three trials is used in the analyses.

2.2.2. Outcome measure

The Speech-in-noise test (SNT) (Smits et al, 2004) was initially developed as a functional self-test for screening for hearing loss via telephone. At a later stadium, it also became possible to do the test via the Internet. The test measures the Speech-Reception-Threshold (SRTTn: signal-to-noise ratio in dB corresponding to 50% intelligibility) in noise. Before the test started, respondents were allowed to adjust the volume of the speaker to an optimally understandable level. Respondents with hearing aids were asked to take off their hearing aid(s), because it was technically impossible to perform the test while wearing them. Respondents were asked to listen to 23 different monosyllabic digit triplets in noise (e.g. 3, 6, 5, randomly chosen from the total set of 80 triplets) via headphones in both ears. After each triplet the respondent was asked to repeat the numbers out loud. The interviewer pressed the corresponding numbers on the telephone pad. In case the respondent did not understand (part of) the triplet, they were encouraged to guess. When the respondent gave a correct response (all three digits correct), the signal-to-noise ratio decreased by 2 dB, and when the response was incorrect the signal-to-noise ratio increased by 2 dB. The average signal-to-noise ratio (SNR) was calculated for the last twenty presentations. The signal-to-noise ratio ranged from -12 dB to +8 dB; this range was estimated to be enough to perform SRTTn measurements for the majority of normal-hearing and hearing-impaired people (Smits & Houtgast, 2005). As an example, a score of -5.0 dB SNR means that the respondent understands 50% of the speech correctly when the mean level of the speech is 5.0 dB below the level of the noise (www.lasa-vu.nl).

2.2.3. Potential confounders

The following variables were considered potential confounders: baseline age, sex, education, hearing aid use and vision. The data on age and sex were derived from the municipal registries at baseline. Level of education was determined by asking the respondents about their highest level of education they had completed, ranging from primary education (5 years) to university (18 years). The total years of education were used as a continuous variable. Hearing aid use was assessed in the medical interview by asking “Do you usually wear a hearing aid?” (yes/no). Status of vision was derived from several questions in the medical interview, such as “Can you read small print without glasses or contact lenses?” (yes, without difficulty/yes, with some difficulty/yes, with much difficulty/no). This yielded vision scores ranging from 2 to 8, in which lower scores indicate better vision.

2.2.4. Statistical analyses

Differences in baseline characteristics between respondents on T2 and drop-outs between T1 and T2 were tested with the *t* test for normally distributed data and the Mann-Whitney *U* test for skewed data.

First, (partial) correlations were computed by means of Pearson correlation coefficients to examine the cross-sectional association between the four cognitive tests and the SNT. Possible confounders were added to the model to determine their effects on the correlation.

Second, to determine whether cognitive functioning was significantly associated with auditory performance, cross-sectional multiple regression analyses were conducted.

Third, multiple regression analyses were performed to determine the association between absolute changes in cognitive functioning and absolute changes in auditory performance. These analyses will be referred to as longitudinal analyses A. For these longitudinal analyses the following variables were considered possible confounders: age on T1, sex on T1, education on T1, hearing aid use on T1, vision on T1, hearing aid use on T2, vision on T2, and baseline (T1) score of the cognitive test in question.

Finally, to determine whether baseline scores on the cognitive tests were associated with changes in auditory performance, multiple regression analyses were conducted. These analyses will be referred to as longitudinal analyses B. For the second longitudinal analysis the following variables were considered possible confounders: age on T1, sex on T1, education on T1, hearing aid use on T1, vision on T1, hearing aid use on T2, vision on T2, and baseline (T1) score of the SNT.

In longitudinal analyses A, absolute changes over time were calculated per cognitive measurement (e.g., MMSE-score at T2 minus MMSE-score at T1) and the obtained difference-scores were used as independent variables. In longitudinal analyses B, baseline scores on the cognitive tests were used as independent variables. Absolute changes over time were calculated for the SNT (SNT-score at T2 minus SNT-score at T1), and used as the outcome measure in both longitudinal analyses A and longitudinal analyses B.

In both the cross-sectional and longitudinal models, all potential confounders were tested for their confounding effects. Firstly, it was tested whether they were related to both the independent variable and the outcome measure (i.e. p <.20). Subsequently, they were added one-by-one to the regression model, and those variables that showed a significant confounding effect (≥ 10% change in the unstandardized regression coefficient B) were retained in the model.

All models were tested at the 0.05 significance level. All statistical analyses were conducted using SPSS software for Windows (SPSS Inc., Chicago, IL).

3. Results

The baseline characteristics of the study sample are presented in Table 2. At baseline, 46.5% of the respondents were male, their average age was 74.7 years and their mean level of education was 9.3 years.

Table 1. Baseline characteristics of subjects in the study sample.

	T1 (N=1098)	T2 (N=607)	Absolute mean difference T2-T1
Age at T1 (mean ± S.D.)	74.7 ± 7.2	73.1 ± 6.2	
Gender, male, *n* (%)	511 (46.5)	273 (45.0)	
Education in years (mean ± S.D.)	9.3 ± 3.3	9.5 ± 3.3	
Vision (mean ± S.D.)	2.4 ± 0.9	2.2 ± 0.7	
Hearing aid, *n* (%)	117 (10.7)	54 (8.9)	
Speech-in-noise test (SNT) (median)	-5.6 dB	-5.8 dB	0.7 dB ± 1.9
General cognitive functioning (MMSE) (mean ± S.D.)	27.4 ± 2.5	27.9 ± 2.0	-0.6 ± 2.3
Information processing speed (Coding) (mean ± S.D.)	24.6 ± 7.1	26.4 ± 6.5	-1.6 ± 3.5
Fluid intelligence (RCPM) (mean ± S.D.)	18.2 ± 3.8	19.1 ± 3.4	-0.7 ± 2.9
Episodic memory (15 Words Test) (mean ± S.D.)	8.8 ± 2.6	9.4 ± 2.5	-1.1 ± 2.2

Baseline characteristics show that drop-outs between T1 and T2 (*n*=491) were significantly older, in comparison to respondents that participated in T2 (76.6 vs. 74.7

years, *p*<.001), were less educated (9.0 vs. 9.3 years, *p*=.013), had poorer vision (2.5 vs. 2.4, *p*=.003) and worse median SNT-scores (-5.2 vs. -5.6 dB, *p*=.005). Also they performed worse on the MMSE (26.8 vs. 27.4, *p*<.001), the Coding Task (22.4 vs. 24.6, *p*<.001), the Raven Coloured Progressive Matrices (17.0 vs. 18.2, *p*<.001) and the 15 Words Test (8.1 vs. 8.8, *p*<.001).

Pearson's correlation coefficients (*r*) show that there were significant but small negative correlations between the cognitive measures and the SNT. The correlation coefficients were adjusted for possible confounders age, sex, level of education, hearing aid use and vision. The correlation between general cognitive functioning (MMSE) and SNT was the highest (*r*=-.145, *p*<.001), directly followed by information processing speed (Coding Task) (*r*=-.144, *p*<.001). The correlation between fluid intelligence (RCPM) and the SNT was the lowest (*r*=-.115, *p*<.001), and the correlation between episodic memory (15 Words Test) and SNT was intermediate (*r*=-.125, *p*<.001).

The findings of the cross-sectional regression models are shown in Table 2. Both an unadjusted model and a model corrected for significant confounders are presented.

Table 2. Association between cognitive performance and SNT (at T1).

SNT	Unadjusted β[a]	Adjusted β	*p*-value
MMSE	-.289	-.150[b]	.000
Coding	-.121	-.049[c]	.000
RCPM	-.168	-.073[c]	.000
15 Words Test	-.298	-.110[c]	.000

[a] Unstandardized regression coefficients
[b] Adjusted for age, hearing aid use, education and vision
[c] Adjusted for age, sex, education, hearing aid use and vision

The results show significant negative associations between cognitive functioning and auditory performance after adjustment for the relevant confounders. In particular, a negative association was found between SNT-score and MMSE-score, Coding Task-score, RCPM-score and 15 Words Test-score. For the MMSE-score, the association indicates that a 1 unit increase in cognitive score is associated with a -.150 unit decrease in SNT-score. Since lower SNT-scores indicate better auditory performance, this means that better cognitive functioning is associated with better auditory performance. Reversely, a 1 unit decline in cognitive score would be associated with a .150 unit increase in SNT-score, indicating poorer auditory performance.

The findings of the longitudinal analyses A are shown in Table 3. Both an unadjusted model and a model corrected for significant confounders are presented.

Table 3. Association between differences in cognitive performance over 3 years of follow-up and differences in auditory performance over 3 years of follow-up.

SNT	Unadjusted β[a]	Adjusted β	*p*-value
MMSE	.069 (*p*=.046)	.075 [b]	.032
Coding	-.005 (*p*=.812)	-.013 [c]	.553
RCPM	.025 (*p*=.360)	.008 [d]	.755
15 Words Test	-.027 (*p*=	-.051 [d]	.138

[a] Unstandardized regression coefficients
[b] Adjusted for education at T1
[c] Adjusted for SNT at T1, hearing aid use at T1 and education at T1
[d] Adjusted for SNT at T1

The results show that there was a significant positive association between the longitudinal differences in MMSE-scores and the longitudinal differences in SNT scores. All other results were not statistically significant. The positive association between longitudinal differences in MMSE-scores and longitudinal differences in SNT-scores indicates that a 1 unit longitudinal increase in MMSE is associated with a 0.075 unit longitudinal increase in SNT. Since higher SNT-scores indicate poorer auditory performance, this means that longitudinally an increase in cognition, as measured by the MMSE, is associated with a decrease in auditory performance. However, the found effect is only very small.

The findings of the longitudinal analyses B are presented in Table 4. An unadjusted model and a model corrected for significant confounders are presented.

Table 4. Association between baseline cognitive performance and differences in auditory performance over 3 years of follow-up.

SNT	Unadjusted β[a]	Adjusted β	*p*-value
MMSE	-.008 (*p*=.849)	-.050 [b]	.215
Coding	.008 (*p*=.499)	-.007 [b]	.608
RCPM	-.012 (*p*=.593)	-.030 [b]	.231
15 Words Test	.009 (*p*=.784)	-.025 [b]	.424

[a] Unstandardized regression coefficients
[b] Adjusted for SNT at T1, hearing aid use at T1, hearing aid use at T2 and education at T1

The results show that there were negative associations between baseline cognitive scores and differences in SNT-scores over three years of follow-up. This would mean that an increase in cognition is associated with a decrease in SNT-score, indicating better hearing, and vice versa. However, these associations were not statistically significant.

4. Discussion

The present population-based study explored the cross-sectional and longitudinal association between cognitive functioning and auditory performance. The results showed small but significant correlations between cognitive functioning, as measured by four cognitive tests (the Mini-mental State Examination, the Coding Task, the Raven Coloured Progressive Matrices and the 15 Words Test), and auditory performance as measured by a speech-in-noise test (SNT). Cross-sectional regression analyses showed significant negative associations between cognitive functioning and auditory performance. The results demonstrate that in older persons poorer cognitive scores are associated with higher and thus poorer auditory scores, and vice versa. Longitudinal analyses A only yielded a significant positive association between the differences in MMSE-scores and the differences in SNT-scores. The results show that smaller differences in MMSE-scores over time are associated with bigger differences in SNT-scores over time. This indicates that poorer cognitive functioning over time is associated with better hearing over time, and vice versa. The direction of this association is unexpected could not be explained easily. Further research is necessary to investigate this unexpected association. Longitudinal analysis B yielded no significant results.

When studying the association between cognitive functioning and auditory performance, the question is which types of tests are best and will yield the strongest results. Akeroyd (2008) found no less than 7 test categories to measure auditory performance (sentences, words, syllables, phonemes, babble, noise and quiet). Additionally, there is also a lot of diversity within these categories (e.g. unadjusted words, time-compressed words, speeded-spelling of words). Gennis et al. (1991) reported the use of audiometry and the ability to hear finger friction at 2 cm as methods to measure auditory performance. As for the cognitive tests, Akeroyd (2008) found at least 27 types of tests that were used, which can be categorized as follows: general scholastic ability or achievement, standard Intelligence Quotient (IQ) tests, tests of memory, tests of working memory, simple and choice reaction times, visual analogs of speech reception, and miscellaneous tests (Akeroyd, 2008).

Akeroyd (2008) argued that working memory tests yield significant results, as opposed to tests that measure general cognitive abilities. The sensitivity of a working memory measure could be explained by the fact that working memory is closely related to speech processing, since it is “the *workspace* for thinking and [it] serves to hold the earlier words in a sentence or phrase as the listener attempts to construct the meaning" (CHABA report, 1988). Furthermore, Daneman and Carpenter (1980) have shown a positive correlation between working memory processing capacity and listening comprehension. The most significant effects are found when researchers use sentences in noise. Furthermore, Akeroyd claims that measuring comprehension of speech would yield stronger results than solely measuring speech identification (i.e., hearing (Kiessling et al, 2003)), because the first would be more cognitively demanding.

The results of the present study only partially support Akeroyds (2008) claims. Whereas Akeroyd mentions that general cognitive measures are unlikely to yield significant results, in the present study cross-sectional associations were found between the SNT and all four types of cognitive tests, including the MMSE which measures general cognitive functioning. Furthermore, Akeroyd claimed that sentences in noise would yield the most significant effects, but the current study has shown that the measurement of words (i.e., digit triplets) in noise also yields significant cross-sectional results. An import point that has to be taken into consideration when interpreting the results of the present study, is the fact that the SNT measures digit triplets in noise, and that it measures only that specific type of speech in that specific type of noise. The SNT is not automatically a general tool for measuring all types of speech-in-noise, and therefore one has to be careful to generalize the results from this test (Smits, 2005).

In comparison to other studies, there are some differences and some similarities in the results and conclusions. Gennis et al. (1991) concluded that there seems to be a significant positive association between cognitive functioning in demented patients and auditory performance, but that this association is inconclusive in normal elderly people since some studies reported to have found a significant association (Granick et al, 1976; Cutler & Grams, 1988), whereas others reported no significant association after adjustment for relevant confounders (Herbst & Humphrey, 1980; Thomas et al, 1983; Jones et al, 1984; Vesterager et al, 1988). However, the present cross-sectional results demonstrate an association between cognitive functioning and auditory performance in a study sample that as a whole is categorized as representative for normal community-dwelling elderly in the Netherlands. The difference between the current results and the conclusion that was drawn by Gennis et al. (1991) could be explained by the smaller study samples in those studies that did not find an association in normal elderly (samples ranging from 71 to 657 participants). Additionally, the usage of different cognitive tests (e.g., self report of memory loss) than those used in the current study could explain the differences in the results. However, Gennis et al. (1991) also reviewed two studies that used the same measures as the current study: Granick et al. (1976) used the Raven Coloured Progressive Matrices to measure cognitive functioning in normal elderly people and Uhlmann et al. (1989) used the MMSE to measure cognitive functioning in normal elderly people. These two studies found significant associations between cognitive functioning and auditory performance.

Two studies that investigated the association between cognitive functioning and auditory performance in a longitudinal design were Uhlmann et al. (1986) and Peters et al. (1988). Both studies found significant associations over time between MMSE-scores and auditory performance. However, both studies used demented patients in their study samples, which may have yielded more significant results than when using non-demented patients. Furthermore, Uhlmann et al. (1986) used the ability to hear finger friction at 2 cm distance to measure auditory performance. This is a very subjective and unstandardized test. Therefore, the results of the study by Uhlmann et al. (1986) should be interpreted with great caution. Recently, Humes (2002) conducted a longitudinal study on the association between aided and unaided auditory performance and cognitive functioning in 171 elderly adults. He found that the strongest predictor of auditory performance was ‘hearing loss’, followed by cognitive factors.

In the present study only a significant longitudinal association was found between differences in MMSE scores and differences in SNT scores. All other longitudinal associations were statistically insignificant. The reason for not having found many significant longitudinal associations could be due to several factors. First of all, it is possible that the cognitive tests that were used did not pose great demands on the linguistic skills of the respondents. This supports Akeroyds (2008) claim that it may be useful to measure working memory, since working memory is more closely related to language processing. The second reason could be that the cognitive and auditory scores in the current sample were too high and the changes over time too small to find many significant associations. The three year follow-up time may have been insufficient to establish significant changes in cognitive functioning and auditory performance. Furthermore, the minimal changes in the current sample may have been diluted by imprecision of the measuring instruments. The test-retest reliability of the SNT for example is estimated to be better than 1 dB (Smits, 2005). This is a small difference, but it may still have had an influence on the results of the current study.

Finally, it is also possible that a longitudinal association between cognitive scores and SNT scores simply does not exist, and that cognitive functioning and auditory performance are unrelated over time.

Valentijn et al. (2005) have summarized four hypotheses on the association between cognitive and sensory functioning. The results of the present study do not clearly support these hypotheses, nor do they discard them. The current cross-sectional results do however provide some evidence for Akeroyds (2008) hypothesis that listeners use 'top-down' skills to process and comprehend language. This entails that listeners use their knowledge of the world, their understanding of syntax and semantics and their understanding of the rules of conversation to segment the speech stream, in order to understand the meaning of the sentence (CHABA report, 1988). They also use this knowledge and experience to resolve what is confusing or missing in the speech stream (Akeroyd, 2008). As is shown by the cross-sectional regression analyses in this study, a higher cognitive score is associated with a higher auditory score, and a lower cognitive score is associated with a lower auditory score. This implies that cognitive performance predicts auditory performance. Translated to a 'top-down' perspective, this would mean that a higher performance at the 'top' is associated with a higher performance at the 'bottom', and reversely a lower performance at the 'top' is associated with a lower performance at the 'bottom'. This means in other words that better knowledge of the world, better understanding of syntax and semantics and better understanding of the rules of conversation will lead to a better capability to segment the speech stream and to understand its meaning. Reversely, poorer knowledge and experience will lead to a poorer ability to segment the speech stream. This is to some extent reflected in the current cross-sectional results.

Strengths of the present study are the large study sample and the use of longitudinal data. Furthermore, the study sample is representative of community-dwelling elderly in three geographic areas in the Netherlands. However, there are also some limitations that should be discussed. Firstly, those respondents that were lost to follow-up were the older and poorer functioning persons. Drop-outs had significantly lower scores on the cognitive tasks and had lower scores on the SNT. This may have lead to an underestimation of the (longitudinal) associations between cognitive functioning and auditory performance. Secondly, there were respondents in the study sample that unexpectedly showed increases in cognitive scores and/or auditory score over time. The reasons for these increases have not been investigated, but it is evident that this may have had an influence on the results. Finally, the data of the Speech-in-noise test (Smits et al. 2004) were positively skewed. First, it was attempted to correct this by computing the natural logarithm (LN) of the data. However, the speech-reception-threshold (SRT) is a logarithmic scale in itself, and therefore using a logarithm of a logarithm as an outcome measure yielded results that were virtually uninterpretable. Therefore, it was decided to use the untransformed skewed data as the outcome measure. A drawback of this decision is that the assumption of normal distribution of the data, which is required for regression analyses, was not completely met in the cross-sectional analysis. However, since the scatter plots showed that the residues were reasonably normally distributed, we felt confident that a regression analysis would be tolerable in this particular situation. In the longitudinal analyses the data were normally distributed, so regression analyses could be conducted since all assumptions were met.

In conclusion, this study has shown a cross-sectional association between cognitive functioning and auditory performance. The results suggest that when testing ones auditory performance, cognitive measures might have to be taken at the same time, since they may influence the auditory scores. Future research should focus on the study of longitudinal associations and should use a representative and homogeneous study sample, in which substantial cognitive decline is present over time to elucidate the presence of a causative association.

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