Chandrashekar and Nagaraj
The Egyptian Journal of Otolaryngology (2024) 40:85
https://doi.org/10.1186/s43163-024-00630-4

The Egyptian Journal of Otolaryngology

ORIGINAL ARTICLE **Open Access**

Executive functions in mid-life adults with mild sensorineural hearing loss compared with age-matched controls with normal hearing

Pooja Chandrashekar[1*] and Hema Nagaraj[1]

Abstract

Purpose This study explores the relationship between sensorineural hearing loss (SNHL) in mid-life adults and cognitive function, focusing on executive functions. Given the projected rise in dementia cases, identifying modifiable risk factors for cognitive decline is imperative. SNHL has emerged as a potential risk factor, with hearing loss accounting for a substantial portion of dementia cases. However, the cognitive implications of SNHL in mid-life adults are not well understood.

Method The study examined 50 participants, 25 with bilateral unaided mild SNHL (AHL) and 25 with normal hearing (ANH). A battery of audiological assessments and cognitive tests, including the Trail Making Test (TMT), was administered. TMT measures included direct scores (completion time and errors) and derived scores (difference, ratio, proportion, sum, and multiplication scores).

Results The AHL group displayed significantly poorer peripheral hearing compared to the ANH group, as reflected in pure-tone audiometry, speech reception thresholds, and speech identification scores. Significant differences were observed in all direct and derived TMT measures except for the ratio and proportion scores. This suggests that while overall cognitive disturbances were evident in the AHL group, they were not exclusive to executive function deficits. Notably, we did not identify any statistically significant effects of hypertension, diabetes, smoking, alcohol consumption, or physical activity on TMT scores.

Conclusion This study highlights the potential impact of SNHL on cognitive function in mid-life adults. Mid-life SNHL is associated with cognitive differences, emphasizing its role as a modifiable risk factor for future cognitive decline. This research underlines the need for further investigation into the cognitive effects of aided hearing and a multidisciplinary approach to understanding these alterations in cognitive function.

Keywords Sensorineural hearing loss, Cognitive function, Executive functions, Dementia risk, Mid-life adults

Background

It is commonly known that hearing loss is prevalent in older adults and sensorineural hearing loss (SNHL) is a widespread occurrence on a global scale [62]. The prevalence of hearing loss doubles with each successive decade of increased age and mostly begins during mid-life. For instance, approximately 27% of adults in their mid-life experience hearing loss [15]. However, there is a scarcity of research highlighting the increasing prevalence of hearing loss in mid-life. Such findings present potential opportunities for early intervention to mitigate the significant future impact of age-related hearing loss [84]. Hearing loss in mid-life not only acts as a potential risk factor for dementia [23] in older adults by influencing changes in brain structures but

*Correspondence:
Pooja Chandrashekar
p.chshkr@gmail.com
[1] Department of Speech-Language Sciences, All India Institute of Speech and Hearing, Mysuru, India

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

is also associated with increased late-life atrophy over time, particularly in specific temporal lobe structures involved in auditory processing and AD [6]. In recent studies, a strong link has been established between dementia and hearing loss, with the latter being identified as an independent but also a promising modifiable risk factor for incident dementia [3, 19, 20, 31–33, 37, 39, 56, 57, 69, 72, 81]. The causal mechanisms are discussed in detail elsewhere [86].

To date, there is limited data [63] that attempted to identify subtle cognitive changes that occur in early midlife adults (between 45 and 55 years of age) with hearing loss as it has been observed that 55 years is the youngest mean age [32] at which the presence of hearing loss increased the risk of dementia. Previous studies have considered a wide array of neuropsychological tests to assess the cognitive abilities of their study participants including tests to examine the executive function (EF) [61]. There are three core components of EF, namely, cognitive flexibility, inhibitory control, and working memory [65]. The Trail Making Test (TMT) [71] is a test that employs these components for its execution. Part A of the TMT primarily evaluates attention, visual scanning, speed of eye-hand coordination, and information processing whereas Part B assesses working memory and EF, specifically the capacity to transition between sets of stimuli [54, 64, 73]. Previous studies have demonstrated that TMT can effectively predict changes in individuals with MCI [14, 26, 38] and AD [16]. The TMT has been sensitive to EF [73] impairments and has consistently produced significant findings across multiple clinical [8, 36, 51, 67] and aging population [60]. Moreover, its sensitivity also extends to various neurological processes [53, 64, 76]. Although completion times for TMT-A and B are regularly used in clinical practice, derived scores are also employed for interpretive purposes [54, 64, 78]. Another noteworthy measure of interest is the number of performance errors [4, 79]. The most commonly utilized derived scores include the difference score (B-A), the ratio score (B/A), and the proportion score (B-A/A). The rationale for employing these scores is twofold. Firstly, they serve to mitigate the influence of individual variability in Part B by utilizing each subject as their own control. Secondly, these scores help eliminate the contributions of motor speed and visual scanning speed by comparing Part B to Part A. Several authors have contended that these derived scores represent more refined measures of EF compared to the direct scores [5, 9, 18, 24, 41–43, 50, 73, 79]. While the derived scores are recognized for their sensitivity to frontal lobe damage [79], it is worth noting that they emphasize distinct characteristics. The difference score is found to be influenced by demographic characteristics when compared to the ratio score [24, 42, 50]. Conversely, the sum and multiplication scores offer indicators of overall cognitive performance rather than focusing solely on EF [43, 51]. The present study aimed to compare the performance of the TMT direct scores (i.e., completion time and performance errors for Part A and Part B) and derived scores (i.e., difference, ratio, proportion, sum, and multiplication scores) in mid-life adults with and without hearing loss. It was hypothesized a priori that adults with hearing loss would perform similarly to those without hearing loss on the TMT.

Methods

Study participants

The sample size for the present study was calculated using G*power analyses [27] utilizing the mean and standard deviation obtained from the pilot study at the significance level (α) of 0.05 and power of the test (1-β) at 0.80 [75]. The analysis prescribed a sample size ranging from 5 to 10. Due to the availability of participants, a total of 50 participants were recruited for the study consisting of 25 adults with bilateral unaided mild hearing loss (AHL) (13 female,mean age: 50.44 ± 2.84 years) and 25 adults with normal hearing (ANH) (13 female,mean age: 49 ± 3.29 years). A purposive sampling method was employed to collect samples for the present study. Demographic information for both groups is reported in Table 1.

All participants were right-handed, native Kannada speakers, with normal or corrected vision. None of them had a history of communication disorders, learning disabilities, neurological disorders, traumatic brain injury, or psychiatric disorders. Individuals with a history of substance abuse, use of psychoactive medications, known causes of hearing loss such as noise exposure, injuries, ototoxicity, unilateral or bilateral continuous tinnitus, those using hearing aids and experiencing significant vision issues such as untreated cataracts, macular

Table 1 Demographic characteristics of participants

	AHL group	ANH group
Total *N*	25	25
Age in years mean (SD)	50.44 (2.84)	49 (3.29)
Gender *N*	13F/12M	13F/12M
Hypertension *N*(%)	6 (24.0)	7 (28.0)
Diabetes *N*(%)	8 (32.0)	3 (12.0)
Smoking *N*(%)	2 (8.0)	2 (8.0)
Alcohol consumption *N*(%)	4 (16.0)	3 (12.0)
Physical activity *N*(%)	12 (48.0)	11 (44.0)

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing. *F* indicates female, *M* indicates male degeneration, glaucoma, and retinopathy were excluded. All the participants had more than 12 years of formal education and underwent the Montreal Cognitive Assessment (MoCA), with a cut-off score of < 26 to eliminate potential cognitive impairment. Information regarding the presence or absence of hypertension, diabetes, smoking, alcohol consumption, and regular physical activity was also noted as these factors play an important role in accelerating cognitive decline.

Ethical considerations

The present study was approved by the Ethical Committee for bio-behavioral research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The participants were recruited for the study only after obtaining their written consent as per the ethical guidelines for bio-behavioral research involving human subjects of the All India Institute of Speech and Hearing [11]. All the participants and their caregivers were explained about the procedure and the approximate duration required for the tests. They were assured of safety during testing and confidentiality regarding their personal details.

Audiological evaluation

All participants underwent a comprehensive audiological assessment that included an otoscopic examination to eliminate the possibility of outer ear diseases, tympanometry to confirm the normal functioning of the middle ear, reflexometry to identify any abnormalities in the reflex pathways, along with both pure-tone and speech audiometry tests. Air conduction (AC) and bone conduction (BC) pure-tone thresholds were assessed in both ears using the modified Hughson-Westlake procedure [13]. Thresholds were recorded for octave frequencies ranging from 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC, respectively. The hearing thresholds for AC and BC were obtained using TDH-50P supra-aural headphones (Telephonics, Farmingdale, NY, USA) and a B71 bone vibrator (Radioear, KIMMETRICS, Smithsburg, MD, USA), respectively. The pure tone audiometry was carried out using Inventis Piano, a two-channel diagnostic audiometer (Inventis, 35127 Padova, Italy).

Speech recognition threshold (SRT) was obtained through live presentation of a standardized spondee word list in Kannada [70] which was within ± 12 dB HL of the pure-tone average threshold. Speech identification scores in quiet were determined using standard phonemically balanced word lists in the Kannada language [89] developed at the All India Institute of Speech and Hearing. All participants achieved speech identification scores exceeding 90% in quiet conditions. Tympanograms were obtained using a 226-Hz probe tone. Acoustic reflex thresholds were assessed for both ipsilateral and contralateral responses at frequencies of 500 Hz and 1000 Hz. It was confirmed that all participants exhibited normal middle ear function in both ears, as evidenced by 'A' type tympanograms and normal ipsilateral and contralateral acoustic reflex thresholds at 500 Hz and 1000 Hz. The immittance evaluations were performed using GSI-Tympstar Middle ear Analyzer (Grason Stadler Inc.-GSI-61,Milford, NH, USA). All tests were conducted in acoustically treated rooms.

The hearing sensitivity of the ANH group was within normal limits of ≤ 15 dB HL at frequencies 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC. The hearing sensitivity of the AHL group was between 25 dB HL to 40 dB HL [17] for similar frequencies for both AC and BC which was diagnosed as bilateral mild SNHL by a certified Audiologist.

Since the age difference equivalent to the cognitive decline linked with a 25-dB rise in hearing loss is 7 years, [55] adults with unaided mild SNHL were considered for the study. The study was carried out during the initial visit of the participants where they were diagnosed as having hearing loss for the first time. All the participants with reduced hearing sensitivity were directed towards hearing rehabilitation which mostly suggested the use of hearing aids.

EF tests

Trail making test

Part A Participants were instructed to connect 25 numbered circles sequentially by drawing lines connecting them as quickly and correctly as possible. Timing commenced as soon as participants were prompted to begin using a stopwatch. The examiner pressed the stopwatch as quickly and accurately as possible as soon as the participant started and finished the test. Whenever an error was made the examiner crossed out the erroneous line and provided immediate feedback. The test was discontinued if the participant failed to complete the test within 300 seconds.

Part B Participants were instructed to connect encircled numbers and letters, alternating between the two sequences (e.g., 1-A-2-B, and so on) consecutively in a progressive manner, up to the number 13. Commencing the timing, providing feedback for errors, and discontinuing the test were conducted following the same procedures as those employed in Part A. The entire TMT test including both Part A and B was administered in accordance with the protocol outlined by Bowie and Harvey [12]. Both tests were carried out using paper and pen in a single session. Instructions were provided at the most comfortable level (MCL) through the audiometer and the participants were required to repeat the instructions before starting the test to ensure they understood the test instructions. If the participants were able to repeat the instructions appropriately, the examiner began the test. If they failed to, instructions were given to the participants again. The test was commenced only after the participants repeated the test instructions correctly. We adhered to this protocol with the concern towards participants with hearing loss as they took part in the study in an unaided condition, and our goal was to confirm that the reduction in hearing sensitivity did not impede their comprehension of the task instructions.

Scoring

The TMT yielded a total of four direct scores and five derived scores. The direct measures of performance encompassed the time taken to complete both Part A and B, as well as the number of errors made during these tests separately. From the direct scores, five derived scores were computed that included difference score (B-A), ratio score (B/A), proportion score (B-A)/A, sum score (A+B), and multiplication score (AxB/100). It is important to note that lower direct scores and higher derived scores indicate superior performance on the test.

Statistical analysis

Data analysis of this study was performed using the Statistical Package for Social Science (SPSS) version 20. Demographic data and the TMT scores are presented using descriptive statistics including the mean, standard deviation, sum of ranks, and mean ranks. Following data analysis for normality of distribution by the Shapiro–Wilk test, it was found that the TMT scores were not normally distributed. Since the scores were not normally distributed, alternative non-parametric tests have been employed in the present study. Mann-Whitney *U* test was carried out to find out the significance of the difference between AHL and ANH groups on the selected dependent variables that included both direct and derived TMT scores.

Results

Significant differences were observed between AHL and ANH groups for all the audiological measures as indicated by the Mann-Whitney *U* test in Table 2. The smaller U values obtained for the differences in values of audiological measures were all found to be significant at the .001 level. The mean ranks obtained for AHL and ANH groups were 38 and 13 respectively for right PTA (p = .001), the mean ranks obtained for left PTA for AHL and ANH groups were 38 and 13 respectively with a significance level of .001, and the mean ranks obtained for the right SRT were 37.98 and 13.02 respectively (p = .001), the mean ranks obtained for left SRT measure for AHL and ANH groups were 38 and 13 respectively with the significance level of .001. In all of the above-mentioned audiological measures, the AHL group had significantly higher values than the ANH group. However, in the case, the mean ranks obtained for right SIS percent were 16.10 and 34.90 with a significance level of .001 as well as in the case mean ranks obtained for left SIS percent were 13.72 and 37.28 with a significance level of .001, whereas the ANH group had higher values than AHL.

Mann-Whitney *U* test revealed significant differences between ANH and AHL groups (refer Table 3) in most of the TMT measures except for B/A (p = .377), and B-A/A (p = .377). In the case of TMT A, the mean ranks obtained for 13.96 and 37.04 with a significance level of .001, the mean ranks obtained for TMT A error were 22.32 and 28.68 respectively with a significance level of

Table 2 Results of audiological measures between AHL and ANH groups

Audiological measures	AHL group Mean (SD)	ANH group Mean (SD)	ANH group mean rank (sum of ranks)	AHL group mean rank (sum of ranks)	*p* value
Right PTA (dB HL)	10.40 (4.02)	33.26 (4.49)	38 (950)	13 (325)	.001*
Left PTA (dB HL)	10.55 (3.21)	33.20 (4.23)	38 (950)	13 (325)	.001*
Right SRT (dB HL)	5.66 (4.15)	30.60 (6.17)	37.98 (949.50)	13.02 (325.50)	.001*
Left SRT (dB HL)	4.62 (3.20)	33.20 (6.10)	38 (950)	13 (325)	.001*
Right SIS (%)	99.68 (1.10)	94.64 (3.77)	16.10 (402.50)	34.90 (872.50)	.001*
Left SIS (%)	99.84 (0.80)	93.44 (3.02)	13.72 (343)	37.28 (932)	.001*

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing. *PTA (dB HL)* = pure-tone average (decibels hearing level), *SRT (dB HL)* = speech reception threshold (decibels hearing level), *SIS* = Speech Identification Score

* $p < .001$

Table 3 Results of Mann-Whitney *U* test for TMT scores between AHL and ANH groups

TMT measures	ANH group Mean rank (sum of ranks)	AHL group Mean rank (sum of ranks)	*p* value
TMT A	13.96 (349)	37.04 (926)	.000*
TMT A error	22.32 (558)	28.68(717)	.038*
TMT B	14.60(365)	36.40(910)	.000*
TMT B error	21.10(527.50)	29.90(747.50)	.025*
B-A	19.16(479)	31.84(796)	.002*
B/A	27.32(683)	23.68(592)	.377
B-A/A	27.32(683)	23.68(592)	.377
A+B	13.52(338)	37.48(937)	.000*
AxB/100	13.32(333)	37.68(942)	.000*

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing, *TMT A* Trail-making test Part A, *TMT B* Trail-making test Part B

* $p < 0.05$

.038, the mean rank obtained for TMT B were 14.60 and 36.40 respectively with the significance level of .025, the mean ranks obtained for TMT B error were 21.10 and 29.60 respectively with the significance level of .025. The mean ranks obtained for ANH and AHL groups for B-A parameter were 19.16 and 31.84 with a significance level of .002. The mean ranks obtained for A+B parameters were 13.52 and 37.48 with a significance level of .001. Lastly, the mean ranks obtained for AxB/100 measure were 13.32 and 37.68 respectively with the significance level of .001. In all the above-mentioned measures AHL group had higher values than the ANH group. Box plots for direct and derived measures of TMT are depicted in Figs. 1 and 2 respectively.

Discussion

This study examined differences in performance on direct and derived measures of TMT between AHL and ANH groups. We found significant differences between the two groups on PTA, SRT, and SIS scores. The AHL group exhibited higher scores on PTA and SRT, and lower SIS scores relative to the ANH group, indicating poorer peripheral hearing. Findings revealed significant group differences in all the direct and derived measures of TMT except the ratio and proportion scores.

The findings of the present study are in agreement with the previous studies employing TMT B, where group differences were observed between older adults with hearing loss and normal hearing controls [1, 7, 40, 56, 57, 75].

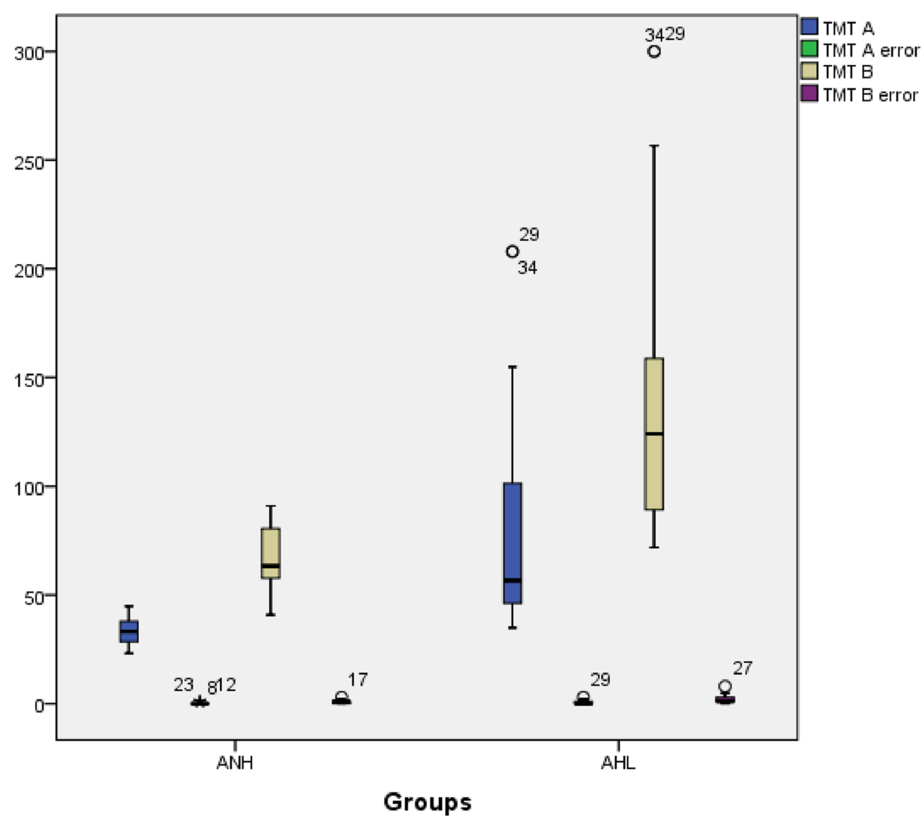

Fig. 1 Box plots for direct measures of TMT for ANH and AHL groups

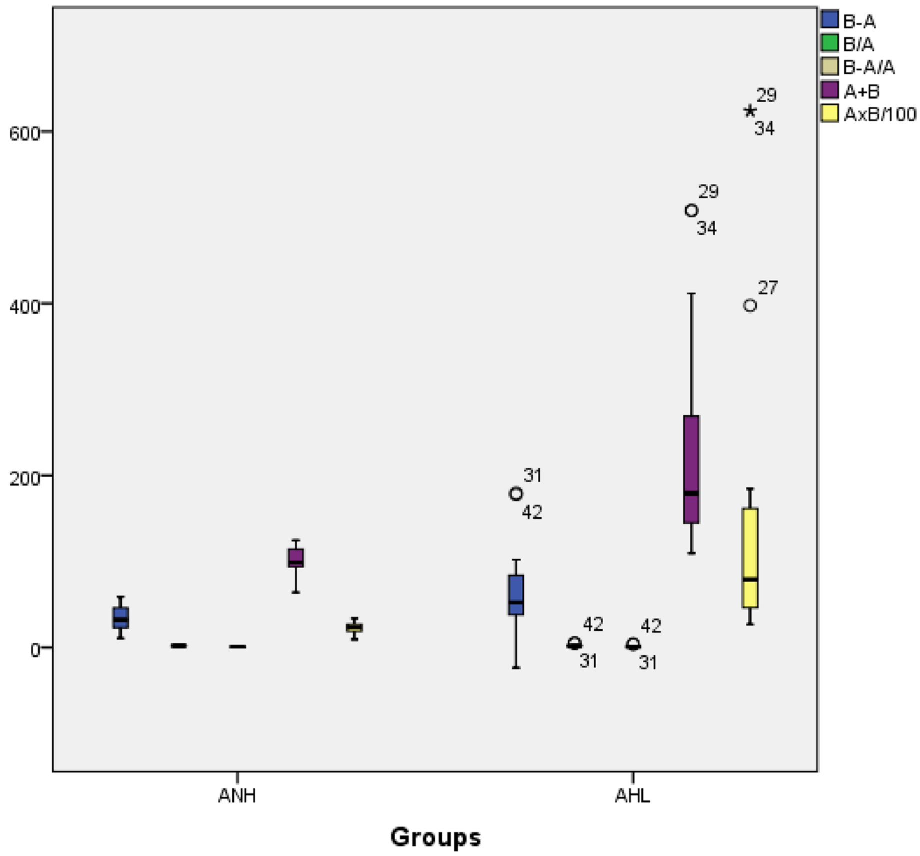

Fig. 2 Box plots for derived measures of TMT for ANH and AHL groups

The control group performed significantly better than the clinical group in the raw completion times, number of errors, and derived scores that resulted from difference, sum, and multiplication. However, we did not find any significant difference in the ratio and proportion scores. This variability introduces the challenge of interpreting TMT performance, especially in relation to the derived scores which could be attributed to the subject's demographic characteristics. The ratio and proportion scores are considered to be the most sensitive indices within the TMT for identifying deficits in EF. This is due to their lower susceptibility to the influence of demographic characteristics, as indicated by previous studies [18, 50]. While we did observe a notable distinction in TMT measures, we did not identify a variance in the most sensitive EF indices. This suggests the effect of demographic characteristics play an important role in disrupting the overall cognition that does not exclusively pertain to EF.

In this light, we observed the effect of hypertension, diabetes, smoking, alcohol consumption, and physical activity on TMT scores. However, our analysis did not yield any statistically significant findings. Since these conditions are previously known to be associated with increased dementia risk [59], the present results are contrary to the previous studies. One possible explanation for our results is that prior studies have primarily focused on considerably older populations compared to the participants in our study. Additionally, the long-standing effects of these conditions could potentially exert a detrimental influence on cognitive abilities over time [45].

The present study adds to the extensive research over decades that has indicated a link between sensory abilities, particularly hearing and cognitive performance [10, 44, 49, 58, 68, 80, 88]. This association suggests that cognitive decline due to hearing loss may commence during midlife, emphasizing its pivotal role as a significant modifiable risk factor for the subsequent development of dementia. While the acceptance of hearing loss as an independent and modifiable risk factor for dementia is widespread, its specific impact in midlife as a potential harbinger of cognitive consequences in later life remains inadequately elucidated [23]. An alternative perspective suggested that midlife hearing loss could potentially be an outcome of preclinical neurodegeneration rather than a causal factor [48, 85]. The present study supports this notion by demonstrating significant differences in the TMT measures between the ANH and AHL groups.

One of the significant reasons for the results obtained in the present study could potentially be attributed to methodological disparities in the previous studies, particularly in the context of audiological assessments. For instance, certain studies relied on self-assessed hearing measurements from participants, and the criteria for hearing loss varied. In some studies, the range of normal hearing was considered up to 25 dB [55]. In our study, we meticulously adhered to a rigorous and standardized methodology. Notably, at the time of our investigation, the participants had not undergone any form of auditory rehabilitation, such as the use of hearing aids. In contrast, the participant groups in prior studies displayed heterogeneity, with some individuals employing hearing aids while others did not, considering that hearing loss is a reversible sensory deficit [66]. By diligently controlling for these variables, our study potentially unveiled significant differences across various TMT measures, shedding light on the impact of these methodological distinctions.

The observed variation in TMT performance could be due to alterations in auditory pathways resulting from peripheral hearing loss, which in turn may affect cognitive control [29]. Cohort studies suggest that even a mild degree of hearing loss may increase the risk of cognitive decline in individuals who initially exhibit cognitive intactness but are hearing-impaired at the baseline [21, 22, 30, 32, 39, 55–57, 83, 87]. The literature has put forth several potential hypotheses to elucidate this connection between hearing loss and cognitive changes including the cognitive load on perception hypothesis, the information degradation hypothesis, the sensory deprivation hypothesis, and the common cause hypothesis [82]. These mechanisms have the potential to deplete cognitive resources that are otherwise available for various cognitive functions. This, in turn, could contribute to the depletion of cognitive reserve and hasten the emergence of preclinical indicators of cognitive decline leading to dementia [2, 77].

On a similar line, a study among Chinese centenarians and oldest-old adults revealed that the occurrence of cognitive decline and depression was notably higher among individuals with HL compared to those without. Participants with HL exhibited significantly lower cognitive test scores, suggesting more pronounced cognitive decline, and experienced higher levels of depression [28]. Further, a systematic review of twenty-three studies found a substantial link between HL and mild cognitive impairment (MCI) [52]. The majority of studies reviewed indicated a notable association between peripheral HL and MCI. This finding is significant as EF is one of the areas commonly impacted in individuals with MCI which again supports the link between HL and subsequent cognitive decline. Research focusing on performance within distinct cognitive areas, such as processing speed, episodic memory, and EF, rather than overall cognitive assessments, has revealed moderate connections with hearing loss across these domains [40]. Numerous cohort studies and meta-analyses have highlighted a correlation between SNHL and cognitive impairment. Specifically, using pure tone audiometry, HL has been linked to lower scores across various neuropsychological tests evaluating multiple cognitive domains, including memory, language, and EF [74]. This association has been consistently observed across both small and large observational studies [25, 34, 46], as well as in cross-sectional and longitudinal population-based studies. Recent studies investigating the link between hearing loss and cognitive decline have utilized EF tests including TMT, indicating its effectiveness in this context [31]. A recent study demonstrated that steady assessments of fluid reasoning which is a part of EF and pure-tone auditory function showed considerable alteration over about seven years. During this timeframe, there was a decline in metabolic health and cognitive abilities, alongside an increase in hearing thresholds. These results suggest that significant age-related changes occur across various functional domains, even among middle-aged who are relatively healthy. Furthermore, the study found that lower cognitive performance correlated with elevated audiometric thresholds [35]. Another study that reviewed structural MRI studies revealed that HL is associated with accelerated atrophy of both total and regional brain volumes, along with reduced white matter integrity. Additionally, resting-state and task-based functional MRI studies indicated alterations in spontaneous neural activity and brain functional connectivity. It was concluded that these changes affect brain regions involved in auditory, language, cognitive, and affective processing independently of age [47]. From this perspective, it is clearly evident that HL impacts cognitive performance through a series of physiological changes that ultimately hinder brain function.

Limitations and future directions

To the best of our knowledge, this is the first study to investigate EF in midlife adults exclusively using TMT measures. While these tasks provide valuable insights, they may not fully capture the complexity of cognitive processes affected by SNHL. It is important to note that participation in our study was limited to individuals with untreated hearing loss. Further investigation is necessary to delve into the effects of aided hearing on EF, as well as to determine whether aided hearing can ameliorate these changes. The current study utilized a cross-sectional design, limiting the ability to establish causal relationships between mild SNHL and EF deficits using the TMT. Conducting longitudinal studies to track cognitive changes over time can provide insights into the progression of EF deficits and how they relate to the severity and duration of SNHL. Such studies could also explore whether interventions such as hearing aids or cognitive training programs influence the trajectory of cognitive changes. Studies investigating cognitive function across various levels of hearing loss, ranging from mild to severe can better understand how auditory impairment impacts executive functioning. The study may have also had specific sample characteristics that limit the generalizability of findings to broader populations. A comprehensive understanding of the alterations found in the present study necessitates a multidisciplinary investigative approach encompassing behavioral, neuroimaging, and electrophysiological methodologies.

Conclusion

This study delves into the cognitive consequences of SNHL in mid-life adults, focusing on executive functions. While the research confirms that SNHL is linked to overall cognitive disturbances, the impact is not exclusive to executive function deficits, suggesting a broader cognitive influence. The results obtained in the present study accentuate the importance of early intervention for mid-life hearing loss, shedding light on a potential avenue for preventing cognitive decline and mitigating the future burden of dementia.

Acknowledgements
Not applicable.

Authors' contributions
PC conceived and designed the study, collected and analyzed the data, and drafted and edited the manuscript. HN assisted in the study design, provided critical revisions to the manuscript, and edited the manuscript. Both authors read and approved the final manuscript.

Funding
There was no funding received for the present study.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The present study was approved by the Ethical Committee for bio-behavioral research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The research study adhered to all ethical guidelines and regulations, ensuring informed consent, confidentiality, and protection of participants' rights throughout the research process.

Consent for publication
The participants were recruited for the study only after obtaining their written consent for publication as per the ethical guidelines for bio-behavioral research involving human subjects of the All India Institute of Speech and Hearing.

Competing interests
The authors declare that they have no competing interests.

Received: 26 October 2023 Accepted: 12 July 2024
Published online: 05 August 2024

References

1. Alattar AA, Bergstrom J, Laughlin GA, Kritz-Silverstein D, Richard EL, Reas ET, Harris JP, Barrett-Connor E, McEvoy LK (2020) Hearing impairment and cognitive decline in older, community-dwelling adults. J Gerontol 75(3):567–573. https://doi.org/10.1093/gerona/glz035
2. Albers MW, Gilmore GC, Kaye J, Murphy C, Wingfield A, Bennett DA, Boxer AL, Buchman AS, Cruickshanks KJ, Devanand DP, Duffy CJ, Gall CM, Gates GA, Granholm AC, Hensch T, Holtzer R, Hyman BT, Lin FR, McKee AC, Morris JC, Petersen RC, Silbert LC, Struble RG, Trojanowski JQ, Verghese J, Wilson DA, Xu S, Zhang LI (2015) At the interface of sensory and motor dysfunctions and Alzheimer's disease. Alzheimer's Dement 11:70–98
3. Amieva H, Ouvrard C, Giulioli C, Meillon C, Rullier L, Dartigues JF (2015) Self-reported hearing loss, hearing aids, and cognitive decline in elderly adults: a 25-year study. J Am Geriatr Soc 63(10):2099–2104. https://doi.org/10.1111/jgs.13649
4. Amieva H, Sylviane L, Auriacombe S, Rainville C, Orgogozo J, Dartigues J et al (1998) Analysis of error types in the Trail Making Test evidences an inhibitory deficit in dementia of the Alzheimer type. J Clin Exp Neuropsychol 20:280–285
5. Arbuthnott K, Frank J (2000) Trail Making Test, Part B as a measure of executive control: validation using a set-switching paradigm. J Clin Exp Neuropsychol 22:518–528
6. Armstrong NM, An Y, Doshi J, Erus G, Ferrucci L, Davatzikos C, Deal JA, Lin FR, Resnick SM (2019) Association of midlife hearing impairment with late-life temporal lobe volume loss. JAMA Otolaryngol-HeadNeck Surg 145(9):794–802. https://doi.org/10.1001/jamaoto.2019.1610
7. Armstrong NM, An Y, Ferrucci L, Deal JA, Lin FR, & Resnick S. M. (2020). Temporal sequence of hearing impairment and cognition in the Baltimore Longitudinal Study of Aging. J Gerontol, 75 (3), 574–580. https://doi.org/10.1093/gerona/gly268
8. Ashendorf L, Jefferson AL, O'Connor MK, Chaisson C, Green RC, Stern RA (2008) Trail Making Test errors in normal aging, mild cognitive impairment, and dementia. Arch Clin Neuropsychol 23:129–137. https://doi.org/10.1016/j.acn.2007.11.005
9. Axelrod BN, Aharon-Peretz J, Tomer R, Fisher T (2000) Creating interpretation guidelines for the Hebrew Trail Making Test. Appl Neuropsychol 7:186–188
10. Baltes PB, Lindenberger U (1997) Emergence of a powerful connection between sensory and cognitive functions across the adult lifespan: a new window to the study of cognitive aging? Psychol Aging 12:12–21
11. Basavaraj V, & Venkatesan S. (2009). Ethical guidance for bio-behavioral research involving human subjects. Mysore, India: All India Institute of Speech and Hearing
12. Bowie CR, Harvey PD (2006) Administration and interpretation of the Trail Making Test. Nat Protoc 1(5):2277–2281
13. Carhart R, Jerger JF (1959) Preferred method for clinical determination of pure-tone thresholds. J Speech Hear Disord 24(4):330–345
14. Chapman RM, Mapstone M, McCrary JW, Gardner MN, Porsteinsson A, Sandoval TC, Reilly LA (2011) Predicting conversion from mild cognitive impairment to Alzheimer's disease using neuropsychological tests and multivariate methods. J Clin Exp Neuropsychol 33:187–199
15. Chen DS, Genther DJ, Betz J, Lin FR (2014) Association between hearing impairment and self-reported difficulty in physical functioning. J Am Geriatr Soc 62(5):850–856. https://doi.org/10.1111/jgs.12800
16. Chen P, Ratcliff G, Belle SH, Cauley JA, DeKosky ST, Ganguli M (2001) Patterns of cognitive decline in pre-symptomatic Alzheimer disease: a prospective community study. Arch Gen Psychiatry 58:853–858
17. Clark JG (1981) Uses and abuses of hearing loss classification. ASHA 23:493–500

18. Corrigan JD, Hinkeldey NS (1987) Relationships between parts A and B of the Trail Making Test. J Clin Psychol 43:402–409
19. Davies HR, Cadar D, Herbert A, Orrell M, Steptoe A (2017) Hearing impairment and incident dementia: findings from the english longitudinal study of ageing. J Am Geriatr Soc 65(9):2074–2081. https://doi.org/10.1111/jgs.14986
20. Deal JA, Betz J, Yaffe K, Harris T, Purchase-Helzner E, Satterfield S, Pratt S, Govil N, Simonsick EM, Lin FR (2017) Hearing impairment and incident dementia and cognitive decline in older adults: The Health ABC study. J Gerontol 72:703–709
21. Deal JA et al (2017) Hearing impairment and incident dementia and cognitive decline in older adults: the health ABC study. J Gerontol 72(5):703–709. https://doi.org/10.1093/gerona/glw069
22. Deal JA, Sharrett AR, Albert MS, Coresh J, Mosley TH, Knopman D, Wruck LM, Lin FR (2015) Hearing impairment and cognitive decline: a pilot study conducted within the Atherosclerosis Risk in Communities Neurocognitive Study. Am J Epidemiol 181:680–690
23. Del Vecchio V, Tricarico L, Pisani A, Serra N, D'Errico D, De Corso E, Rea T, Picciotti PM, Laria C, Manna G, Franzè A, Malesci R, Fetoni AR (2023) Vascular factors in patients with midlife sensorineural hearing loss and the progression to mild cognitive impairment. Medicina (Kaunas, Lithuania) 59(3):481. https://doi.org/10.3390/medicina59030481
24. Drane DL, Yuspeh RL, Huthwaite JS, Klingler LK (2002) Demographic characteristics and normative observations for derived-Trail Making Test indices. Neuropsychiatry Neuropsychol Behav Neurol 15:39–43
25. Edwards JD, Lister JJ, Elias MN, Tetlow AM, Sardina AL, Sadeq NA, Brandino AD, Harrison Bush AL (2017) Auditory processing of older adults with probable mild cognitive impairment. J Speech Lang Hear Res 60(5):1427–1435. https://doi.org/10.1044/2016_JSLHR-H-16-0066
26. Ewers M, Walsh C, Trojanowski JQ, Shaw LM, Petersen RC, Jack CR Jr, Hampel H (2012) Prediction of conversion from mild cognitive impairment to Alzheimer's disease dementia based upon biomarkers and neuropsychological test performance. Neurobiol Aging 33:1203–1214
27. Faul F, Erdfelder E, Lang A, Buchner A (2007) GPower 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods 39(2):175–191. https://doi.org/10.3758/BF03193146
28. Feng L, Wu D, Lin J, Li Y, Zhao Y, Zhang P, Yao Y, Fu S (2022) Associations between age-related hearing loss, cognitive decline, and depression in Chinese centenarians and oldest-old adults. Ther Adv Chron Dis 13:20406223221084830. https://doi.org/10.1177/20406223221084833
29. Fortunato S, Forlì F, Guglielmi V, De Corso E, Paludetti G, Berrettini S, Fetoni AR (2016) A review of new insights on the association between hearing loss and cognitive decline in aging. Acta Otorhinolaryngologica Italica 36:155–166
30. Fritze T, Teipel S, Ovari A, Kilimann I, Witt G, Doblhammer G (2016) Hearing impairment affects dementia incidence: an analysis based on longitudinal health claims data in Germany. Plos One 11(5):e0156876
31. Fu X, Eikelboom RH, Tian R, Liu B, Wang S, Jayakody DMP (2022) The relationship of age-related hearing loss with cognitive decline and dementia in a sinitic language-speaking adult population: a systematic review and meta-analysis. Innov Aging 7(1):igac078. https://doi.org/10.1093/geroni/igac078
32. Gallacher J, Ilubaera V, Ben-Shlomo Y, Bayer A, Fish M, Babisch W, Elwood P (2012) Auditory threshold, phonologic demand, and incident dementia. Neurology 79(15):1583–1590. https://doi.org/10.1212/WNL.0b013e31826e263d
33. Gao J, Armstrong NM, Deal JA, Lin FR, He P (2020) Hearing loss and cognitive function among Chinese older adults: the role of participation in leisure activities. BMC Geriatr 20(1):215. https://doi.org/10.1186/s12877-020-01615-7
34. Gates GA, Gibbons LE, McCurry SM, Crane PK, Feeney MP, Larson EB (2010) Executive dysfunction and presbycusis in older persons with and without memory loss and dementia. Cogn Behav Neurol 23(4):218–223. https://doi.org/10.1097/WNN.0b013e3181d748d7
35. Ghisletta P, Dahle CL, Raz N (2023) Age-related hearing loss, cognitive performance, and metabolic risk in healthy adults: a seven-year longitudinal study. J Gerontol 78(3):409–420. https://doi.org/10.1093/geronb/gbac148
36. Giovagnoli AR et al (1996) Trail making test: normative values from 287 normal adult controls. Italian J Neurol Sci 17:305–309. https://doi.org/10.1007/BF01997792
37. Golub JS et al (2017) Observed hearing loss and incident dementia in a multiethnic cohort. J Am Geriatr Soc 65(8):1691–1697. https://doi.org/10.1111/jgs.14848
38. Gomar JJ, Bobes-Bascaran MT, Conejero-Goldberg C, Davies P, Goldberg TE (2011) Utility of combinations of biomarkers, cognitive markers, and risk factors to predict conversion from mild cognitive impairment to Alzheimer disease in patients in the Alzheimer's disease neuroimaging initiative. Arch Gen Psychiatry 68:961–969
39. Gurgel RK, Ward PD, Schwartz S, Norton MC, Foster NL, Tschanz JT (2014) Relationship of hearing loss and dementia: a prospective, population-based study. Otol Neurotol 35(5):775–781. https://doi.org/10.1097/MAO.0000000000000313
40. Harrison Bush A, Lister J, Lin F, Betz J, Edwards J (2015) Peripheral hearing and cognition: evidence from the Staying Keen in Later Life (SKILL) study. Ear Hear 36(4):395–407. https://doi.org/10.1097/AUD.0000000000000142
41. Heaton RK, Nelson LM, Thompson DS, Burks JS, Franklin GM (1985) Neuropsychological findings in relapsing-remitting and chronic-progressive multiple sclerosis. J Consult Clin Psychol 53:103–110
42. Hester RL, Kinsella GJ, Ong B, McGregor J (2005) Demographic influences on baseline and derived scores from the Trail Making Test in healthy older Australian adults. Clin Neuropsychol 19:45–54
43. Horton AM, Roberts C (2001) Derived Trail Making Test indices in a sample of substance abusers: demographic effects. Intl J Neurosci 111:123–132
44. Humes LE (2020) Associations between measures of auditory function and brief assessments of cognition. Am J Audiol 29(4):825-37
45. Humes LE, Busey TA, Craig J et al (2013) Are age-related changes in cognitive function driven by age-related changes in sensory processing? Attention Percept Psychophys 75(3):508–524
46. Idrizbegovic E, Hederstierna C, Dahlquist M, Rosenhall U (2013) Short-term longitudinal study of central auditory function in Alzheimer's disease and mild cognitive impairment. Dement Geriatr Cogn Disord Extra 3(1):468–471. https://doi.org/10.1159/000355371
47. Jafari Z, Kolb BE, Mohajerani MH (2021) Age-related hearing loss and cognitive decline: MRI and cellular evidence. Ann NY Acad Sci 1500(1):17–33. https://doi.org/10.1111/nyas.14617
48. Kivimaki M, Singh-Manoux A (2018) Prevention of dementia by targeting risk factors. Lancet 391:1574–1575
49. Kurylo DD, Corkin S, Allard T, Zatorre RJ, Growdon JH (1993) Auditory function in Alzheimer's disease. Neurology 43:1893–1899
50. Lamberty GJP, Chatel SH, Bieliauskas DM, Linas A (1994) Derived Trail Making Test indices: a preliminary report. Neuropsychiatry Neuropsychol Behav Neurol 7:230–234
51. Lange RT, Iverson GL, Zakrzewski MJ, Ethel-King PE, Franzen MD (2005) Interpreting the Trail Making Test following traumatic brain injury: Comparison of traditional time scores and derived indices. J Clin Exp Neuropsychol 27:897–906
52. Lau K, Dimitriadis PA, Mitchell C, Martyn-St-James M, Hind D, Ray J (2022) Age-related hearing loss and mild cognitive impairment: a meta-analysis and systematic review of population-based studies. J Laryngol Otol 136(2):103–118. https://doi.org/10.1017/S0022215121004114
53. Lezak MD (1995) Neuropsychological Assessment, 3rd edn. Oxford University Press, New York
54. Lezak MD, Howieson DB, Loring DW (2004) Neuropsychological Assessment, 4th edn. Oxford University Press, New York
55. Lin FR (2011) Hearing loss and cognition among older adults in the United States. J Gerontol Series A 66:1131–1136
56. Lin FR, Ferrucci L, Metter EJ, An Y, Zonderman AB, Resnick SM (2011) Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. Neuropsychology 25(6):763–770. https://doi.org/10.1037/a0024238
57. Lin FR, Metter EJ, O'Brien RJ, Resnick SM, Zonderman AB, Ferrucci L (2011) Hearing loss and incident dementia. Arch Neurol 68(2):214–220. https://doi.org/10.1001/archneurol.2010.362
58. Lindenberger U, Baltes P (1994) Sensory functioning and intelligence in old age: a strong connection. Psychol Aging 9:339–355
59. Livingston G, Huntley J, Sommerlad A, Ames D, Ballard C, Banerjee S, Brayne C, Burns A, Cohen-Mansfield J, Cooper C, Costafreda SG, Dias A, Fox N, Gitlin LN, Howard R, Kales HC, Kivimäki M, Larson EB, Ogunniyi A, Orgeta V, Mukadam N (2020) Dementia prevention, intervention, and

care: 2020 report of the Lancet Commission. Lancet 396(10248):413–446. https://doi.org/10.1016/S0140-6736(20)30367-6
60. Llinas-Regla J, Vilalta-Franch J, Lopez-Pousa S, Calvo-Perxas L, Torrents Rodas D, Garre-Olmo J (2017) The Trail Making Test: Association with other neuropsychological measures and normative values for adults aged 55 years and older from a Spanish-speaking population-based sample. Assessment 24(2):183–196. https://doi.org/10.1177/1073191115602552
61. Loughrey DG, Kelly ME, Kelley GA, Brennan S, Lawlor BA (2018) Association of age-related hearing loss with cognitive function, cognitive impairment, and dementia: a systematic review and meta-analysis. JAMA Otolaryngol-Head Neck Surg 144(2):115–126
62. Mathers C, Fat DM and Boerma JT. (2004). "World Health Organization, 2008. The global burden of disease." Retrieved from http://www.who.int/healthinfo/global_burden_disease/GBD_report_2004update_full.pdf
63. Merten N, Fischer ME, Tweed TS, Breteler MMB, Cruickshanks KJ (2020) Associations of hearing sensitivity, higher-order auditory processing, and cognition over time in middle-aged adults. J Gerontol 75(3):545–551. https://doi.org/10.1093/gerona/glz189
64. Mitrushina MN, Boone KL, D'Elia L (1999) Handbook of Normative Data for Neuropsychological Assessment. Oxford University Press, New York
65. Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerter A, Wager TD (2000) The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. Cogn Psychol 41:49–100
66. Panza F, Solfrizzi V, Logroscino G (2015) Age-related hearing impairment: a risk factor and frailty marker for dementia and AD. Nat Rev Neurol 11:166–175
67. Periáñez JA et al (2007) Trail Making Test in traumatic brain injury, schizophrenia, and normal aging: Sample comparisons and normative data. Arch Clin Neuropsychol 22:433–447. https://doi.org/10.1016/j.acn.2007.01.022
68. Pichora-Fuller MK (2015) Cognitive Decline and Hearing Healthcare for Older Adults. Am J Audiol 24:108–111
69. Quaranta N, Coppola F, Casulli M, Barulli O, Lanza F, Tortelli R, Capozzo R, Leo A, Tursi M, Grasso A, Solfrizzi V, Sobbà C, Logroscino G (2014) The prevalence of peripheral and central hearing impairment and its relation to cognition in older adults. Audiol Neuro-Otol 19(Suppl 1):10–14. https://doi.org/10.1159/000371597
70. Rajasekhar B.(1976) Development and standardization of a picture SRT test for adults and children in Kannada. Unpublished Master's Dissertation. University of Mysore
71. Reitan RM (1958) Validity of the trail making test as an indicator of organic brain damage. Percept Motor Skills 8:271–276. https://doi.org/10.2466/pms.1958.8.3.271
72. Rong H, Lai X, Jing R, Wang X, Fang H, Mahmoudi E (2020) Association of sensory impairments with cognitive decline and depression among older adults in China. JAMA Network Open 3(9):e2014186. https://doi.org/10.1001/jamanetworkopen.2020.14186
73. Sanchez-Cubillo I, Perianez JA, Adrover-Roig D, Rodriguez-Sanchez JM, Rios-Lago M, Tirapu J et al (2009) Construct validity of the Trail Making Test: Role of task-switching, working memory, inhibition/interference control, and visuomotor abilities. J Int Neuropsychol Soc 15:438–450
74. Sardone R, Battista P, Panza F, Lozupone M, Griseta C, Castellana F, Capozzo R, Ruccia M, Resta E, Seripa D, Logroscino G, Quaranta N (2019) The age-related central auditory processing disorder: silent impairment of the cognitive ear. Front Neurosci 13:619. https://doi.org/10.3389/fnins.2019.00619
75. Shende, S. A., Nguyen, L. T., Lydon, E. A., Husain, F. T., & Mudar, R. A. (2021). Cognitive flexibility and inhibition in individuals with age-related hearing loss. Geriatrics, 6(1). https://doi.org/10.3390/geriatrics6010022
76. Spreen O, Strauss E (1998) A Compendium of Neuropsychological Tests: Administration, Norms, and Commentary, 2nd edn. Oxford University Press, New York
77. Stahl SM (2017) Does treating hearing loss prevent or slow the progress of dementia? Hearing is not all in the ears, but who's listening? CNS Spectrums 22:247–250
78. Strauss E, Sherman EMS, Spreen O (2006) A compendium of neuropsychological tests: administration, norms, and commentary, 3rd edn. Oxford University Press, New York
79. Stuss D, Bisschop M, Alexander M, Levine B, Katz D (2001) The trail making test: a study in focal lesion patients. Psychol Assess 13:230–239
80. Swords GM, Nguyen LT, Mudar RA, Llano DA (2018) Auditory system dysfunction in Alzheimer disease and its prodromal states: a review. Ageing Res Rev 44:49–59
81. Thomson RS, Auduong P, Miller AT, Gurgel RK (2017) Hearing loss as a risk factor for dementia: a systematic review. Laryngoscope Investigative Otolaryngology 2(2):69–79. https://doi.org/10.1002/lio2.65
82. Uchida Y, Sugiura S, Nishita Y, Saji N, Sone M, Ueda H (2019) Age-related hearing loss and cognitive decline: the potential mechanisms linking the two. Auris Nasus Larynx 46(1):1–9
83. Valentijn SA, van Boxtel MP, van Hooren SA, Bosma H, Beckers HJ, Ponds RW, Jolles J (2005) Change in sensory functioning predicts change in cognitive functioning: results from a 6-year follow-up in the Maastricht Aging Study. J Am Geriatr Soc 53:374–380
84. Wang J, Sung V, le Clercq CMP, Burt RA, Carew P, Liu RS, Mensah FK, Gold L, Wake M (2019) High prevalence of slight and mild hearing loss across mid-life: a cross-sectional national Australian study. Public Health 168:26–35. https://doi.org/10.1016/j.puhe.2018.11.017
85. Warren JD, Bamiou DE (2018) Prevention of dementia by targeting risk factors. Lancet 391:1575
86. Wayne RV, Johnsrude IS (2015) A review of causal mechanisms underlying the link between age-related hearing loss and cognitive decline. Ageing Res Rev 23(Pt B):154–166. https://doi.org/10.1016/j.arr.2015.06.002
87. Wei J, Hu Y, Zhang L, Hao Q, Yang R, Lu H, Zhang X, Chandrasekar EK (2017) Hearing impairment, mild cognitive impairment, and dementia: a meta-analysis of cohort studies. Dement Geriatr Cogn Disord Extra 7:440–452
88. Whitson HE, Cronin-Golomb A, Cruickshanks KJ, Gilmore GC, Owsley C, Peelle JE, Recanzone G, Sharma A, Swenor B, Yaffe K et al (2018) American Geriatrics Society and National Institute on Aging Bench-to-Bedside Conference: Sensory Impairment and Cognitive Decline in Older Adults. J Am Geriatr Soc 66:2052–2058
89. Yathiraj A, Vijayalakshmi CS. (2005). Phonemically balanced word list in Kannada: developed in Department of Audiology

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.